Reduction of Display Artifacts by Random Sampling

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Abstract

The discrete, sequential scanning (sampling) procedures used in electronic displays generate disturbing artifacts such as flicker, Moire-type patterns, and paradoxical motion. Application of the theory of random scanning procedures to displays can reduce these artifacts. The human retina provides an example of a system that uses randomness to avoid sampling artifacts. Though the retina performs a discrete spatial sampling of the stimulus, artifacts are not evident. For example, we do not see Moire patterns when we look at fine gratings. This is because the retinal receptors are positioned randomly, rather than in a regular array. Random sampling avoids conventional aliasing, but introduces noise. Constraints on the random sampling can banish most of the noise to the region above the Nyquist frequency, where it is easily removed by post-sampling low-pass filtering. For visual displays this means that the sampling artifacts can be traded for noise, and this noise can be placed in regions of space-time frequency for which the human visual system has little sensitivity. Here we report that artifacts, especially those associated with motion, are reduced by constrained random sequencing of horizontal scan lines. Three scan line sequencing procedures are compared: a sequential one, a single random sequence repeated, and a new random sequence on each update. The single random sequence flickered least and was almost as good as the new random sequence procedure at minimizing motion artifacts for the display of a vertical line moving horizontally.

Introduction

Sequential scanning artifacts

The usual sequential scanning procedures in television-type displays generate a number of disturbing artifacts. Consider the simplest common scanning procedure: pixels within a line are shown from left to right and lines are shown from top to bottom. This sequence is repeated at the update rate. If the update rate is below the temporal cutoff frequency of the visual system, flicker will be a perceived artifact. Unfortunately, the temporal cutoff frequency of the visual system can be as high as 80 Hz. In addition, keeping the update rate above the temporal cutoff frequency does not ensure an artifact-free display. Movement of either the display content or the eyes of the observer can generate artifacts even when the update rate is well above the visual temporal cutoff frequency because motion can transform temporal artifacts into spatial artifacts.

The window of visibility

Watson and colleagues used the concept of a "window of visibility" in spatio-temporal frequency space to explain how both spatial and temporal resolution combine to require a high update rate in sampled displays of moving objects.[1,2,3] The "window" is a rectangular region in spatio-temporal frequency space which is bounded by the highest spatial and temporal frequencies which are visible. The spatial frequency limit S is a measure of visual acuity in cycles per degree of visual angle, and the temporal limit T is equal to the critical flicker frequency measured in Hz. The observer is insensitive to signal energy outside of the window.

Consider the case of a point of light moving along a straight line at a velocity V, in degrees of visual angle per second. The left side of Figure 1 shows the distribution of light energy in space and time coordinates. It is a line whose slope is the velocity of the point. The right side of Figure 1 shows the distribution of energy in temporal frequency and spatial frequency coordinates, that is, the Fourier transform of the left side. The frequency domain distribution is just a line perpendicular to the space-time domain line. Actually, the representations are three-dimensional; the darkness of the lines can be thought of as representing the amplitudes, which in these cases are line impulse functions. If the image of the moving point is sampled at a constant rate of R Hz, the distributions in the two domains are as illustrated in Figure 2. The process of regular sampling in the space-time domain introduces the usual spectral replicates at multiples of R Hz along the temporal frequency axis.

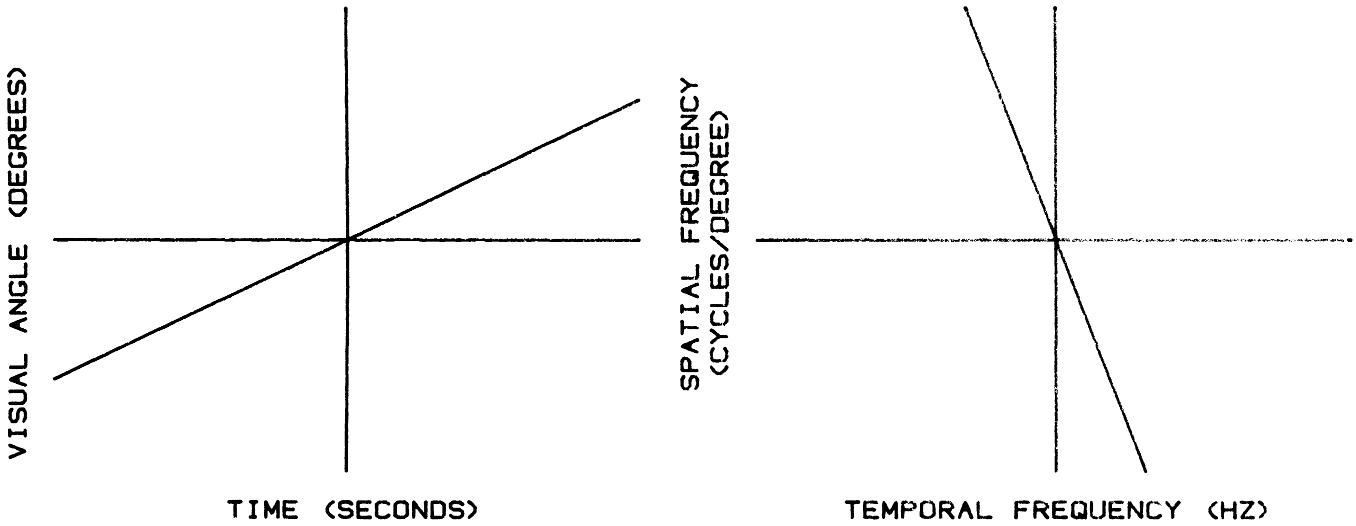

Figure 1. Light distributions for a moving point in space-time (left) and spatio-temporal frequency (right).

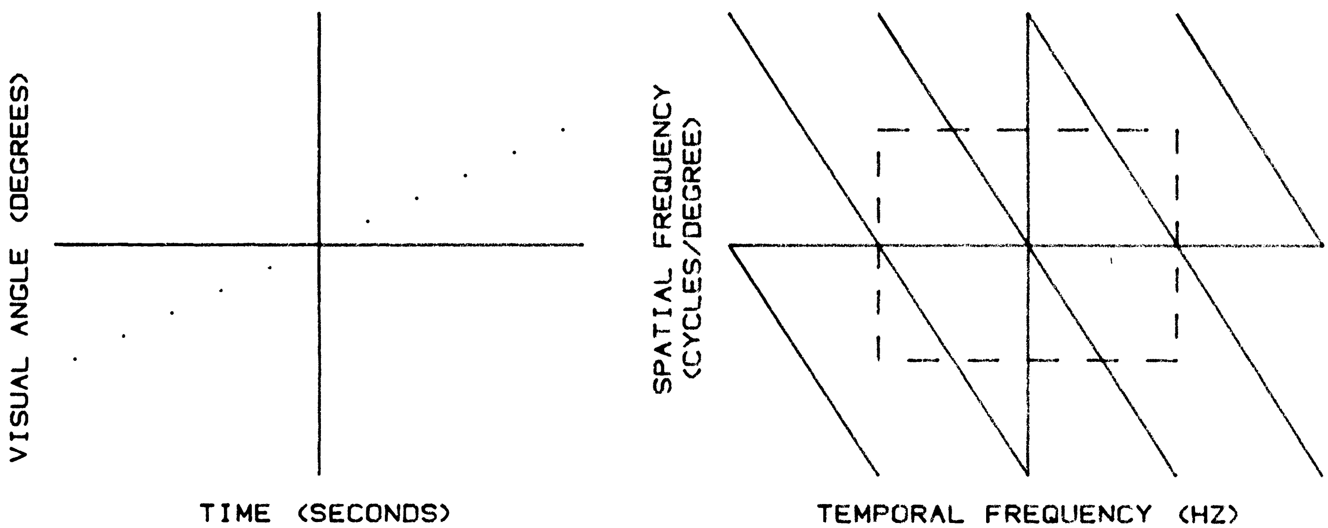

Figure 2. The space-time (left) and spatio-temporal frequency (right) distributions for a sampled moving point with the "window of visibility" indicated with dashed lines in the frequency domain.

If the spectral replicas lie outside the rectangular "window of visibility", then the distribution inside the window is the same as in the unsampled case. In this case, no artifacts will be seen. It is easy to show that there will be no visible artifacts (all spectral replicas are outside the rectangular window) if the update rate is greater than a value Rmin given by the formula,

$$R_{min} = T + V S \quad (1)$$

where T is the temporal frequency limit of the visual system in Hz and S is the spatial frequency limit in cycles per degree. Psychophysical experiments have verified that the required update rate does increase according to Equation (1).[1,2,3]

Random sampling

The standard method of avoiding sampling artifacts without increasing the sampling rate is to low-pass filter the signal before sampling. If the input is from a device like a television camera, the low-pass characteristics of the device itself can be matched to the update rate. This can remove most of the more obvious sampling artifacts, but at the cost (at practical update rates) of less spatio-temporal resolution than that of the visual system. In addition, pre-filtering cannot remove other artifacts such as the line-slant effect to be described below. And in the case of computer-generated imagery, anti-aliasing filtering becomes an expensive, delay-producing proposition.

Information theory tells us that we are bound to lose information if a transmission system with a lower channel capacity is interposed in a transmission system. Since the visual world and the visual system have very large channel bandwidths, affordable video systems are bound to generate artifacts because of the limited number of possible outputs per time period. Merely counting possibilities is not the whole story, however, because the human visual system can not arbitrarily recode its inputs. It is not just the amount of distortion in bits per second that matters. The form of the distortion also matters. In many applications the visibility of the distortion is not as important as whether the distortion generates an incorrect inference of what was present in the visual scene. We propose that the visual impact of sampling artifacts can be reduced by sampling procedures that have a certain amount of randomness. The advantage is that the artifacts in this case tend to take the form of amorphous noise. They do not have the structure evident in regular sampling artifacts which can cause the perception of an erroneous object. Random degradation tends to be seen as a degraded version of the original object rather than as a different object. An example that we will discuss later is the case of a moving line, where sequential sampling generates multiple lines, whereas random sampling generates a cloud which can be regarded as the line appropriately blurred with random noise added. The random nature of light itself and the random nature of the signals in the visual system insure that the visual system has some tolerence for noisy corruption. In addition to the sampling artifacts having the form of noise, it is also possible through constraints on the randomness to put the noise in regions of frequency space where its visual impact is lessened.

Consider the case of completely random (Poisson) sampling. It is usually stated without qualification that if low-pass filtering is not done before sampling, the high frequency components will be permanently confounded with their low frequency reflections about the Nyquist frequency. Actually, of course, this is only true for the case of regular sampling. If the sampling is completely random, all components of the original signal are passed unconfounded except for the addition of wide band random noise.[4] Even more interesting is the fact that if the random sampling is properly constrained, most of the noise can be relegated to high frequency regions where it can be removed by post-sampling low-pass filtering.[5]

Random sampling in the retina

Sampling of this sort is done in the retina of the eye and it prevents the appearance of aliasing artifacts in normal vision. The cones in the central fovea are tightly and regularly packed at a density high enough so that the low-pass filtering by the optics of the eye prevents aliasing. However, only a few degrees off center, the cone spacing has increased to twice the central value, but the optics have hardly changed. Yellott has shown that the spacing of the cones has a sampling transfer function of the type studied by Scott.[6,7] He has also worked out a simple sampling rule which provides a good first approximation to the spacing distribution.[8] The rule is that the cones (sample points) are placed at random with the restriction that no cones can be closer than a certain minimum distance. For the sampling distribution of the retina and for the distribution generated by the simple rule, low spatial frequency information is accurately reproduced. The sampling noise generated by low spatial frequency information appears only in high spatial frequency regions so that it is easily removed by low-pass filtering. Information at spatial frequencies higher than the average Nyquist frequency generates noise which can be seen in appropriate conditions, but is not normally apparent.[9]

Simulation of Programmable Line Sequencing

These discoveries in the spatial domain suggested to us that random sampling might be of use in the spatio-temporal domain of video displays. The ideal display system for testing this idea would be capable of generating a pixel raster in any desired order. We settled for a point-plotting display capable of drawing a vertical row of points in a programmable order. The system was capable of drawing 128 points at an update rate of up to 130 Hz. For this simple vertical line stimulus we are able to study the effects of arbitrary line interlacing techniques of the sort described by Pratt.[10] Three scanning procedures were compared. In procedure SEQ the points were displayed sequentially from top to bottom as in Figure 3. In procedure SRAN a single random sequence was used to order the display of the points, the same random sequence being used for every update as illustrated in Figure 4. In the third procedure, NRAN, a new random sequence was used on each update. To obtain the sequence for the next update a single random sequence was used to permute the sequence used on the previous update. Figure 5 illustrates the NRAN procedure.

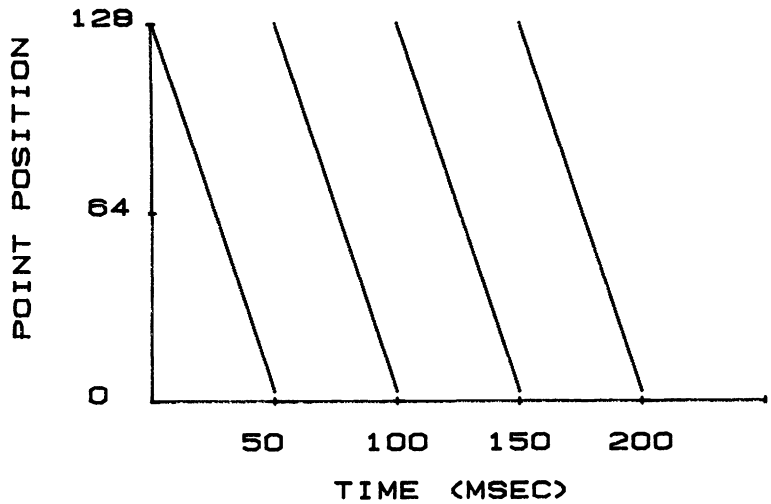

Figure 3. The point sequencing for the sequential procedure (SEQ) at an update rate of 20 Hz.

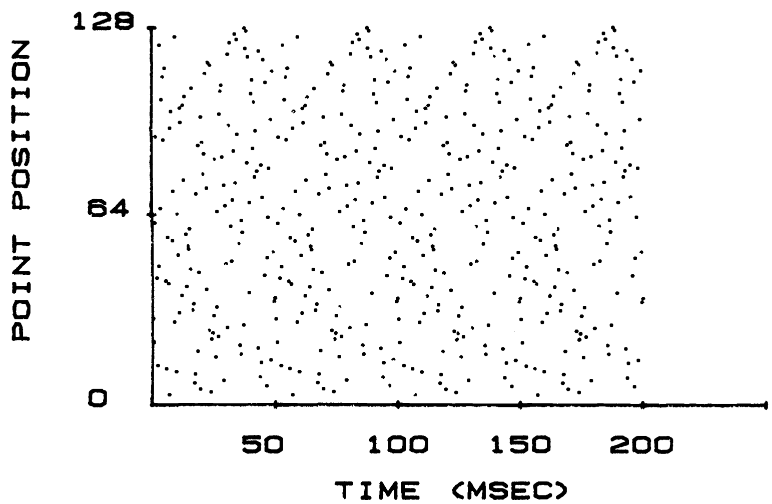

Figure 4. The point sequencing for the single random sequence procedure (SRAN) at an update rate of 20 Hz. Note that the sequence repeats every 50 msec.

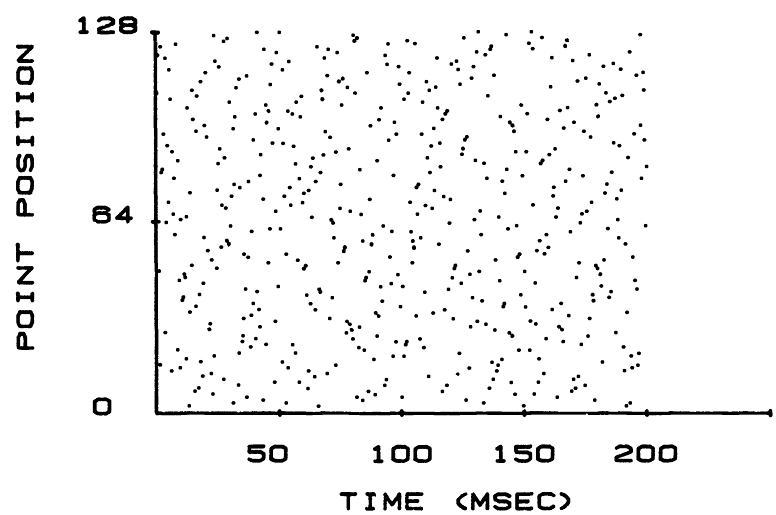

Figure 5. The point sequencing for the procedure in which a new random sequence (NRAN) is used for each update at 20 Hz. Each point is updated in each of the 50 msec intervals, but the order is different each time.

Stationary lines

To see the effects of the three procedures on flicker, a static line was viewed on an HP1345A display from a distance of 1 m. The 128 points of the line spanned 57 mm on the face of the screen. The points were drawn at full brightness and the room illumination (uncontrolled) determined the screen background level and hence the contrast.

As a rough measure, we can define the "flicker threshold" as the frequency at which flicker becomes evident. In these conditions, the flicker thresholds for the three conditions were 25 Hz (SRAN), 35 Hz (SEQ), and 130 Hz or above (NRAN). The NRAN flicker was visible, but minimal, at the upper limit (130 Hz) of the display's range. The NRAN flicker was quite objectionable at 60 Hz. The quality of the flicker is quite different in the sequential and random cases. For SEQ the downward motion becomes dominant as the flicker becomes stronger. For SRAN and NRAN there is a shimmering up and down motion.

If one considers just a refresh of a single point, one would expect the SEQ and SRAN to be the same. The better performance of the SRAN case is thus the result of the interlacing of adjacent points. From the point of view of a single point it may at first not be apparent why the NRAN case is so poor. Since every point is refreshed in every update cycle, the longest interval between refreshes is less than two update periods. One might then expect the NRAN case to be flicker-free at 60 Hz, since the others were flicker-free at 30 Hz. However, this situation illustrates the advantange of the frequency domain analysis. For a single point, the SEQ and SRAN procedures have no energy between 0 Hz and the update rate, whereas the NRAN procedure generates energy density at all frequencies in this interval. For our static vertical line, then, SRAN provided flicker-free viewing at the lowest update rate.

Moving lines

To simulate the display of a moving object being scanned by a various interlace techniques, the points of the vertical line were plotted on the face of a Tektronix 2215 oscilloscope while the horizontal sweep simulated horizontal motion of the line. If the abscissas of Figures 3, 4, and 5 are regarded as horizontal distance along the face of the oscilloscope, the figures show the view of the screen when the horizontal sweep is simulating the display of a line moving across the face of the scope at 50 cm/s. The figures illustrate the fact that the SEQ procedure breaks up the line into multiple slanted lines, whereas the random procedures generate clouds of dots. When the eye fixates a stationary point and the line moves by, the persistence of vision results in about 100 msec worth of lines or cloud being visible.[11,12] In the SEQ case, the multiple lines are inclined at an angle whose cosine is proportional to the velocity. In the random cases the lines remain vertical. In the SRAN case the cloud repeats at the same interval as the line spacing in the SEQ case, but this repetition is much less striking. In the NRAN case the cloud has no apparent structure. For rapid motion, the NRAN procedure is clearly superior. It generates a noisy picture of the blur that a moving line generates. The SRAN procedure is again better than the SEQ procedure because of the lack of tilt and the relative lack of structure in the cloud simulating the blur.

Summary

These results demonstrate that substantial practical advantages can result from the use of random scanning procedures. In a television display situation they can eliminate systematic spatial distortions that arise when the sequential procedure is used to scan moving objects. The use of a single repeated random sequence for line interlacing can lower the flicker threshold frequecy relative to simple sequential line scanning. Of course for the simple line object displayed here, the usual 2:1 interlace technique lowers the flicker threshold even more, but then the line dances up and down a pixel in the static case and generates even more objectionable artifacts in the presence of moving objects. the case of computer-generated video, random scanning can minimize the necessity of synchronizing the computer's display calculations with the display frame rate. More realistic moving objects can be simulated without the use of low-pass spatio-temporal filtering. In some cases the extra expense of another frame buffer for 'ping-ponging' may be avoided. Random interlace techniques seem to be promising candidates for displays demanding high fidelity motion simulation or reproduction, such as those in flight simulators or in-cockpit video displays from infra-red cameras.

Interesting theoretical and empirical questions are suggested by these results. On the theoretical side one would like procedures for constructing sampling schemes which could put the sampling noise in desired regions of spatio-temporal frequency space. On the empirical side, we need improved models of the way that the visual system works so that we can figure out where to "hide" the noise. Finally, we will need efficient implementations of these procedures in hardware.

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