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THE DISPLAY OF DETECTED IMAGES

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ABSTRACT

A model for the signal modulation and noise characteristics of a detector-laser printer system is described. The model is used to express the system NEQ in terms of the separate detector and display stages. A general approach to the analysis of two-stage imaging systems is then described and compared with recent results for x-ray detection via screen-film combinations.

1. INTRODUCTION

Electronic imaging systems usually include several separate stages in order to detect, process, and display image information. Since imaging requirements usually differ from stage to stage, different technologies are often employed such as CCD cameras, photographic film, laser printers, or CRT displays. For applications requiring retention of the detected image information, it is useful to understand the influence of each system component on the image signal-to-noise ratio (SNR) (1,2). System image quality goals can then be expressed in terms of SNR requirements for the final image. Here, we do not address image degradation due to aliasing.

The performance of quantum-limited detectors is often described in terms of their detective quantum efficiency (DQE) (3), and the corresponding SNR characteristics of an image, whether in optical or electronic form, can be expressed in terms of a noise equivalent quantum (NEQ) exposure. As an example of this approach for multistage imaging systems, we consider a detector and a laser printer.

2. MODEL

Consider the detector and laser printer of Figure 1. The detected image is sampled and quantized. After digital processing, the image is printed by converting it to continuous analogue form and modulating the laser exposure while scanning across the recording material line-by-line. The signal modulation characteristics of the laser printer can be expressed in terms of the equivalent spread functions or modulation transfer functions (MTF) of the modulator, laser beam profile, and recording materials. The laser printer MTF can be expressed as (4)

$$T_p(u,v) = M(u,v)\ H(u,v)\ T_f(u,v)\ ,$$

where M and H are the Fourier transforms of the spread functions of the modulator and laser profile, and T_f is the MTF of the recording film. Noise sources include quantization, laser exposure fluctuations, and granularity of the recording materials. The exposure output noise power spectrum is (4)

$$S_t(u,v) = \left[\mu_f^2(Q)\ S_n(u,v) + [S_q(u,v) + S_b(u,v)]\ M^2(u,v)\right]\ H^2(u,v) \ , \quad (1)$$

where S_q, S_n, and S_b are the noise power spectra of the detected image, laser exposure fluctuations, and quantization noise, respectively. Each of the functions must be expressed in terms of the scanning geometry of the exposed recording film. The equivalent output Wiener spectrum, in terms of the optical density of the recorded image, is approximately (5)

$$WS(u,v) = \left[\frac{\gamma \log_{10} e \quad T_f(u,v)}{\mu_t(Q)}\right]^2 S_t(u,v) + WS_f(u,v) \ ,$$

where γ is the slope of the density-log exposure characteristic of the recording film. For our purposes, we assume that the MTF of the recording material is unity over the spatial frequencies of interest.

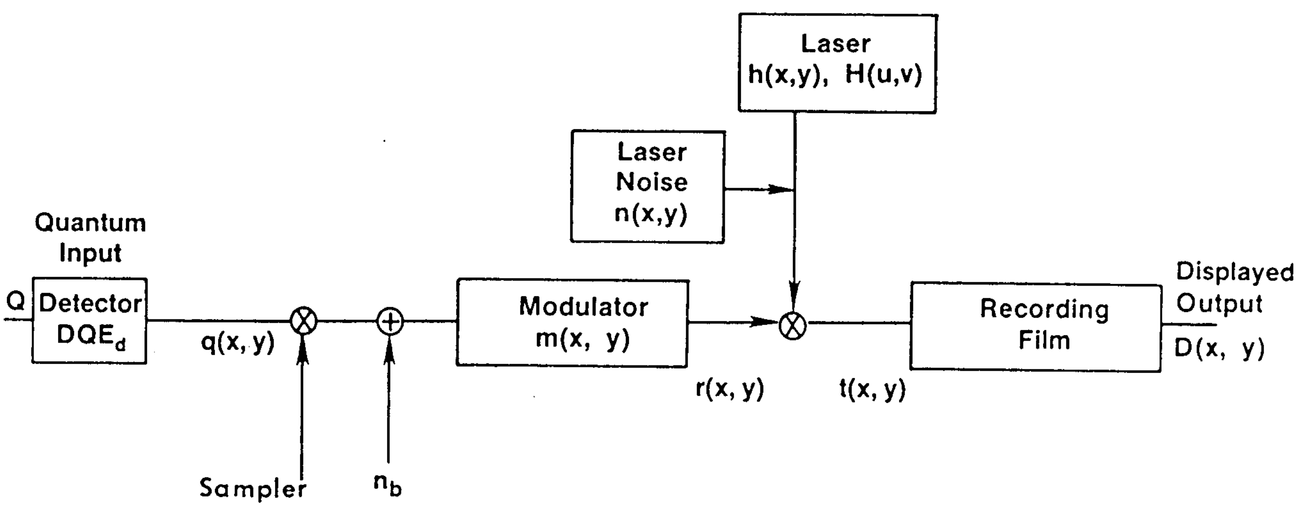

Figure 1. Schematic diagram of detector and laser printer.

The signal and noise characteristics of the laser printer can be described by a single MTF, T_p, an input output gain, G_p , and the noise sources as given in the above model. We can also define a printer Wiener spectrum, WS_p , as that exposure noise power spectrum present when the input, q, is noise free. The exposure noise power spectrum can be expressed as

$$S_t = T_p^2\, G_p^2\, S_q + WS_p \ ,$$

where WS_p is a function of S_n, S_b, and μ_f from equation (1). The NEQ at the exposure output of the detector-printer is, therefore,

$$NEQ_{dp}(Q,u,v) = \frac{NEQ_d(Q,u,v)}{1 + \dfrac{WS_p(Q,u,v)}{S_q(Q,u,v)\ G_p(Q)\ T_p^2(u,v)}} . \qquad (2)$$

For the case where the mean of the detected signal is proportional to the mean exposure, Q, over the range of interest, then equation (2) can be expressed as

$$NEQ_{dp} = \frac{NEQ_d\ NEQ_p\ T_d^2}{NEQ_d\left[1 - \dfrac{NEQ_p}{Q\ G_d}\right] + NEQ_p\ T_d^2} . \qquad (3)$$

This is a general result for imaging systems that are combinations of stages which can be described by linear transfer functions followed by additive stochastic noise sources. Equation (3) shows how the NEQ properties of each stage are combined, and how either stage can limit system NEQ performance.

3. SCREEN-FILM X-RAY IMAGING

The detection and display of x-ray images by a screen-film combination provides an example of a conventional two-stage imaging system. The output NEQ has recently been addressed by a physical model which explicitly includes x-ray absorption, amplification and scattering mechanisms (6,7). The intensifying screen converts the energy of an x-ray quantum into many (m) light photons. For incident quanta, Q, the light exposure to the film is

$$q = Q\ n_1\ m\ n_2 ,$$

where n_1 is the fraction of Q absorbed and n_2 is the fraction of light photons generated, which expose the film.

The imaging characteristics of the screen and the film are not separable to the same extent as the detector and the laser printer. This is primarily due to the *discrete stochastic* scattering and amplification of the intensifying screen (8). The output NEQ can be expressed as (7)

$$NEQ_{sf}(Q,u,v) = \frac{n_1\ Q}{1 + \dfrac{e}{m} + \dfrac{n_1\ Q}{NEQ_f(Q,u,v)\ T_s^2(u,v)}} , \qquad (4)$$

where e denotes the excess of the variance m over the case of a Poisson random variable. Similarly, equation (4) can be expressed in terms of the NEQ of the screen and the film

$$NEQ_{sf}(Q,u,v) = \frac{NEQ_s(Q,u,v)\ NEQ_f(Q,0,0)\ T_s^2(u,v)}{NEQ_s(Q,u,v) + NEQ_f(Q,0,0)\ T_s^2(u,v)} ,$$

where the zero arguments indicate zero spatial frequency.

We can express equation (4) for the screen-film NEQ in the form of equation (3) for the separable two-stage imaging system. This is given by,

$$NEQ_{sf} = \frac{NEQ_s\ NEQ_f\ T_s^2}{NEQ_s\left[1 - \dfrac{NEQ_f}{Q\ m\ n_2}\right] + NEQ_f\ T_s^2} , \qquad (5)$$

which, for realistic values of the model parameters of both screen and film, approximates well to the previously derived result of equation (3), except that detector and printer are replaced by screen and film.

4. CONCLUSIONS

Physical models of signal modulation and noise characteristics can be used to identify fundamental limitations for image detection and display systems. For electronic systems, the problem is often one of choosing the display properties to preserve the detected information. This usually requires a high DQE detector, followed by a display with sufficiently high NEQ (9,10). The approach investigated here allows a natural comparison of the various technologies available, matching detector and display characteristics in terms of SNR and information capacity.

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