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INFORMATION CONTENT MODELING AND SIMULATION OF DIGITAL IMAGING SYSTEMS

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Although digital imaging systems vary, depending on the application, they all must detect, process, and display image information. These steps often require an integration of various technologies into the final design. If a physical model of the system is available, the effect on image quality of the various design choices can be examined. One possible design aim is to retain and display the highest amount of information present in the input image. This can be quantified by combining the statistical characteristics of the input scene and the signal-transfer characteristics of the imaging system <1-7> in a calculation of the output information content, which can be defined <7> in terms of the signal, S(u,v), and noise, N(u,v), spectral densities as

$$H = \frac{1}{2} \iint_{-\infty}^{\infty} \log_2 \left[\frac{S(u,v) + N(u,v)}{N(u,v)} \right] du\, dv \ ,$$

where u and v are orthogonal spatial frequency coordinates, and the units of H are bits/area. System parameters such as sampling interval, detector MTF, and the number of quantization levels can then be chosen to maximize this measure. This definition is strictly applicable only for stationary and independent signal and noise processes, but with reasonable approximations it can be applied to a broad class of practical imaging systems.

MODEL

A general physical model has been developed that cascades power spectra and probability density functions (pdf) of both the signal and signal-plus-noise through a user-defined system image chain. Linear models <8,9> that describe the effects of scanning, sampling, filtering, interpolating, and the addition of noise on power spectra for line-scan and sensor-array imaging are applied casually at each stage of the image chain. In addition, nonlinear point operators such as clipping and thresholding that are not easily described in terms of power spectrum modifications are accommodated by cascading pdf's through the system. The following table shows the effect of several operators on the pdf, mean value, variance, and power spectrum.

SIGNAL	pdf $p(y)$	Mean μ_y	Variance σ_y^2	Spectrum $S_y(u)$
MTF (M)	$T_1(\sigma^2)$	-	$\int M^2 S\,du$	$*M^2$
Linear gain (G)	$T_2(\sigma^2)$	$T_3(\mu)$	$*G^2$	$*G^2$
Clip	Truncate $p(x)$	$\int yp(y)\,dy$	$\int y^2 p(y)\,dy-\mu^2$	$T_4(\sigma^2)$
NOISE				
Random Noise	$\int p_n(y-x\|x)p(x)\,dx$ $y=x+n(x)$	-	$\int y^2 p(y)\,dy-\mu^2$	$+S_n(u)$
Quant. Noise	$T_5(\sigma^2)$	-	$+\sum_j \int (x-x_j)^2 p(x)\,dx$	$T_6(\sigma^2)$
Sample	-	-	-	$+\sum_j S_x(u-\frac{j}{\Delta})$
Periodic Noise	$p(x)\circledast U_1 \circledast .. U_N$	-	$+\sum_i a_i^2/2$	$+\sum_i \delta(u_i) a_i^2/2$

Table - The effects of several model elements on signal and noise propagation through a system. T( ) indicates a point transformation (scaling) as a function of the argument. S(u) is the spectrum, p(x) and p(y) are the input and output pdf's for a given operator, Δ is the discrete sampling interval, U_i is a zero mean uniform pdf whose width is related to the variance of the periodic noise, a_i is the amplitude of the periodic noise, and $\circledast$ represents convolution.

The image chain model allows for definition of the input scene spectrum and pdf. To minimize the software complexity and to account for asymmetric systems, two one-dimensional (horizontal and vertical) calculations of the output information content are performed and the geometric mean is calculated. For each stage independent variables such as the numerical aperture of an optical element, number of bits in an a/d converter, and the dynamic range of an image display are chosen. Linear operators such as filters and additive signal-independent noise are first applied to the spectra and the resultant variances are used to modify the pdf's, making the assumption that such operators do not change the shape or mean value of the pdf, an assumption that is valid except in the case of extreme low-pass filtering where the pdf's tend toward Gaussians. Conversely, operations best described by their effects on the pdf's such as quantization, thresholding, and clipping are applied to the pdf's first, and the resultant variance is used to scale the spectra.

To analyze design tradeoffs in terms of perceived rather than displayed information an optional signal modulation and noise model of the human visual system <10> can be included as a final stage in the image chain. The model adaptively accommodates for variations in pupil diameter, spatial and temporal integration, and neural sensitivity as a function of the mean luminance based on measured noise and MTF data.

SIMULATION

Image simulation has significant value in imaging system design, especially for extremely complex systems. Since for digital imaging systems the effect of signal modulation and noise can be simulated as well as modeled, a one-dimensional simulated output image can be generated that represents a single realization of the ensemble of possible output images, given the statistical characteristics of the input image and the system. The simulated input image consists of two one-dimensional vectors that represent oversampled (i.e., continuous) records of the input exposure versus distance for the horizontal and vertical dimensions. Stationary as well as nonstationary images, such as those consisting of two Gaussian random variables with memory, can be selected, and each vector is randomly generated to be consistent with the chosen signal spectrum and pdf. These are then cascaded through the signal processing steps of the chosen imaging stages, and the output vectors are displayed for comparison.

CONCLUSIONS

A general causal image chain model is presented that can be used to describe monochromatic digital imaging systems. The model has been implemented in software to provide a flexible design and analysis tool. Power spectra and pdf's are cascaded through the system from input scene to displayed or perceived image, and an integrated measure of output information content, in bits/area is calculated. In addition, one-dimensional random realizations of output signals are generated that can be used as interpretation aids in system design studies.

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