Signal and Image Processing Seminar

DESIGN AND QUALITY ASSESSMENT OF FORWARD AND INVERSE ERROR DIFFUSION HALFTONING ALGORITHMS

Ph.D. Defense

Thomas D. Kite

Laboratory for Image and Video Engineering
The University of Texas at Austin

31 July 1998

OUTLINE

- Introduction to halftoning
- Visual quality metrics for forward and inverse halftoning
  - Human visual system
  - Weighted noise metric (WSNR)
  - Modeling other distortions
- Halftoning by error diffusion
  - Linear gain model
  - Modified error diffusion
  - Noise metric
  - Tonality metric
- Inverse halftoning
  - Algorithm design and results
  - Modeling inverse halftoning
  - Quality metrics
- Rehalftoning and interpolation
- Contributions

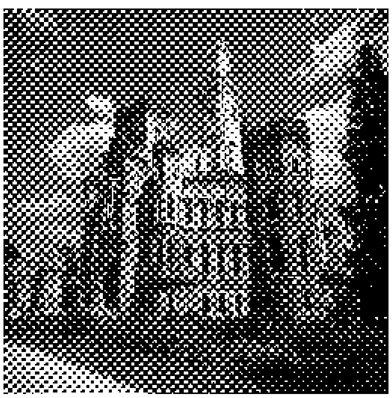
INTRODUCTION: HALFTONING

- Was analog, now digital image processing
- Wordlength reduction for images
  - 8-bit to 1-bit for grayscale
  - 24-bit RGB to 8-bit for color displays
  - 24-bit RGB to CMY for color printers
- Applications
  - Printers
  - Digital copiers
  - Liquid crystal displays
  - Video cards
- Halftoning methods
  - Screening
  - Error diffusion
  - Direct binary search
  - Hybrids

EXAMPLE HALFTONES

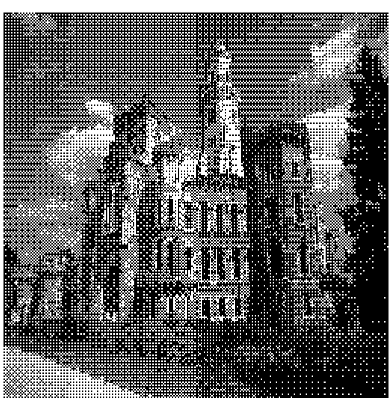
Original image

Direct binary search



Clustered dot screen

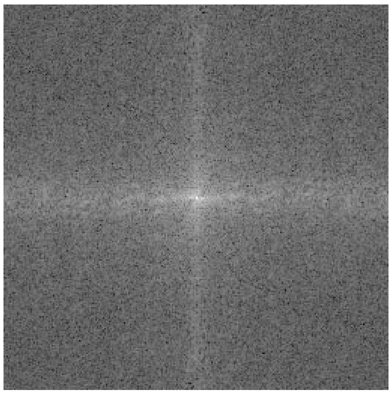
Error diffusion I



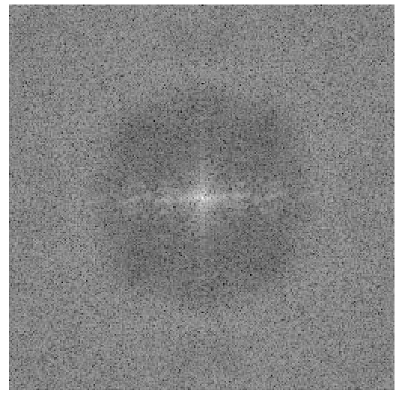
Dispersed dot screen

Error diffusion II

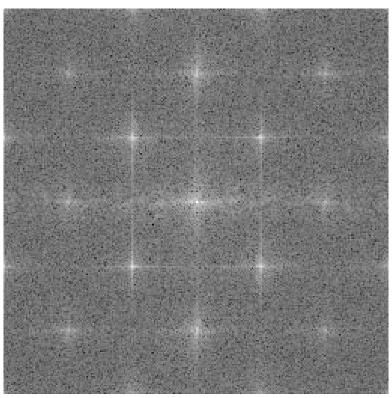
FOURIER TRANSFORMS



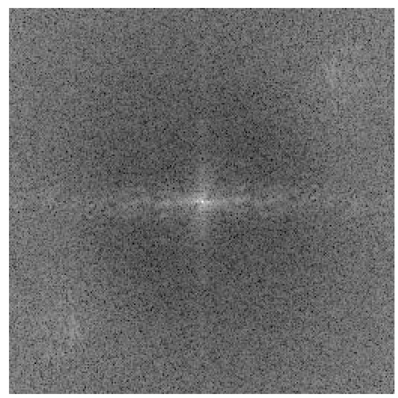
Original image



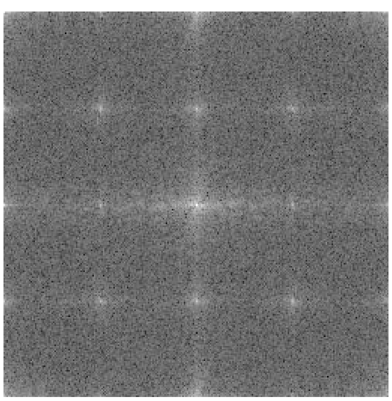
Direct binary search



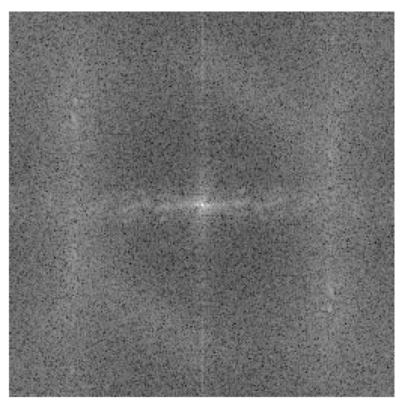
Clustered dot screen



Error diffusion I



Dispersed dot screen



Error diffusion II

PROBLEMS TO BE SOLVED

- Visual quality metrics for forward and inverse halftones
  - Quantify frequency distortion
  - Quantify artifacts
  - Quantify quantization noise
- Modeling error diffusion
  - Develop tractable model
  - Demonstrate accuracy of model
  - Use model to design applications
- Inverse halftoning
  - Develop efficient algorithm
  - Develop model for inverse halftoning

OUTLINE

- Introduction to halftoning
- Visual quality metrics for forward and inverse halftoning
  - Human visual system
  - Weighted noise metric (WSNR)
  - Modeling other distortions
- Halftoning by error diffusion
  - Linear gain model
  - Modified error diffusion
  - Noise metric
  - Tonality metric
- Inverse halftoning
  - Algorithm design and results
  - Modeling inverse halftoning
  - Quality metrics
- Rehalftoning and interpolation
- Contributions

HUMAN VISUAL SYSTEM (HVS)

- Non-linear, spatially varying
- Assuming linearity, spatial invariance explains [Cornsweet 1970]
  - Mach band effect
  - Apparent brightness *vs.* intensity

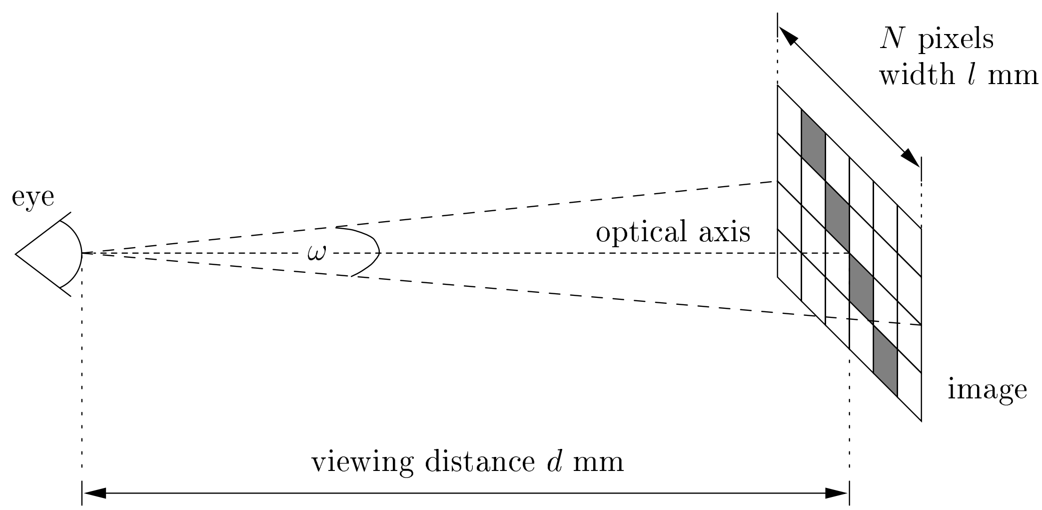
White noise
SNR = 10 dB

Blue (highpass) noise
SNR = 10 dB

- Weight by spatial frequency to quantify visual impact of noise

ANGULAR FREQUENCY

- Sensitivity depends on angular frequency subtended at eye
- Compute angular frequency from image size (pixels), printed image size (mm), viewing distance (mm)



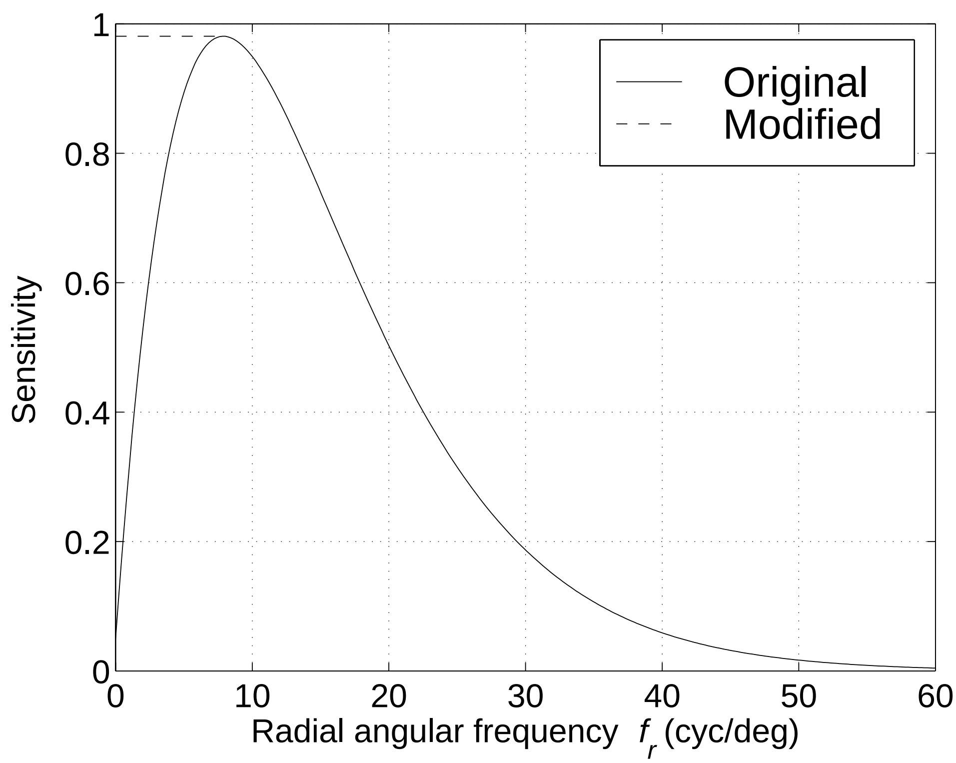
- At Nyquist frequency

$$f_a = \frac{N\pi d}{360 l} \quad \text{cycles/degree}$$

CONTRAST SENSITIVITY (CSF)

- Minimum contrast to distinguish sine grating from uniform field
- Model [Mannos & Sakrison 1974]
- Modification [Mitsa & Varkur 1993]

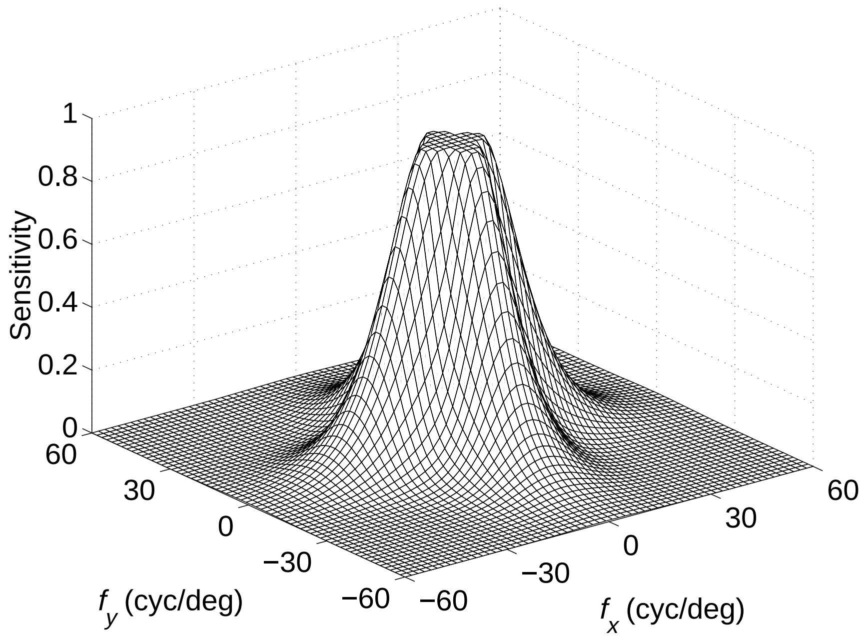
$$\mathrm{CSF} = 2.6\,(0.02 + 0.1 f_a)\, e^{-(0.1 f_a)^{1.1}}$$



- Orientation-independent

WEIGHTED SNR METRIC

- Include orientation (angular dependence) in CSF [Sullivan, Miller & Pios 1993]

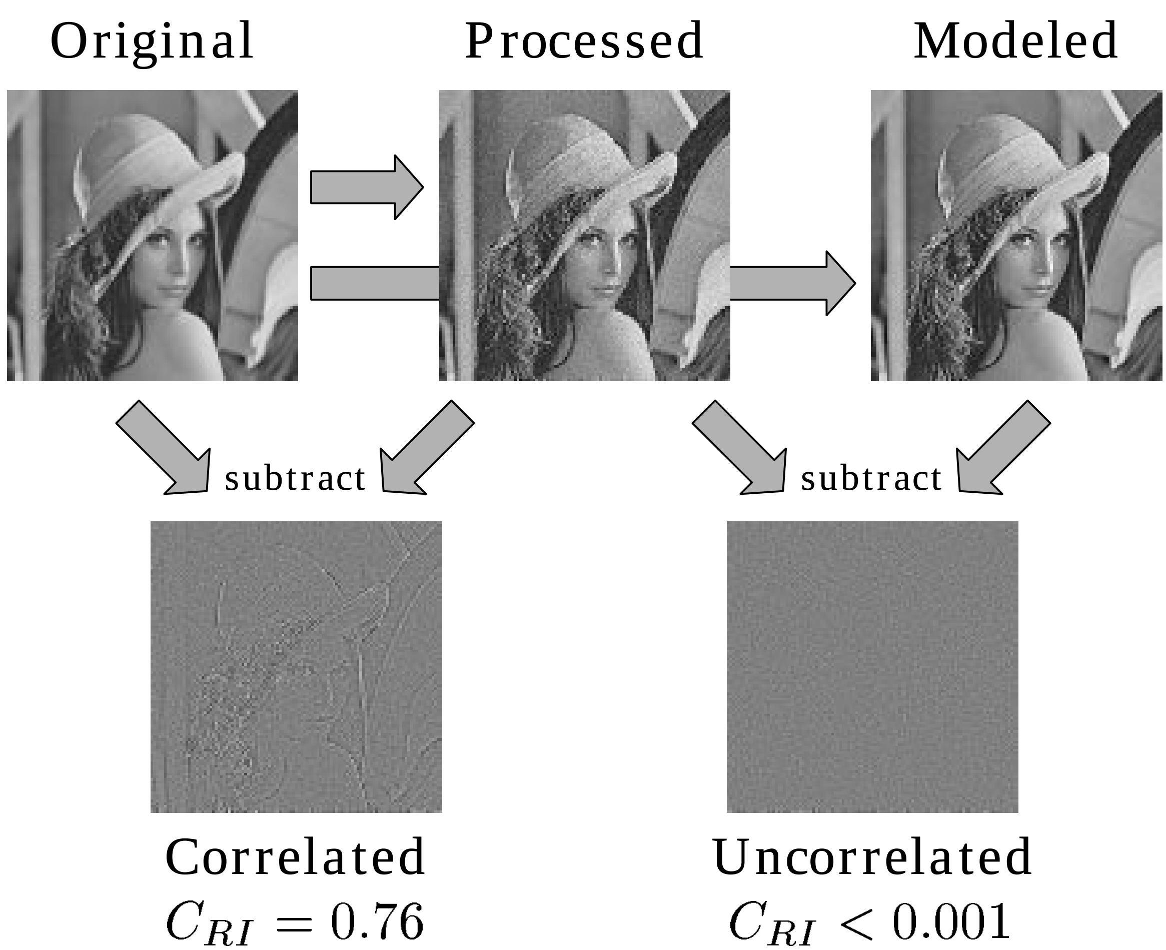


- Compute weighted signal-to-noise ratio between original image *x* and processed image *y*

$$\mathrm{WSNR} = 10\log_{10}\left(\frac{\sum |\mathrm{CSF} \times X(u,v)|^2}{\sum |\mathrm{CSF} \times (X(u,v) - Y(u,v))|^2}\right)$$

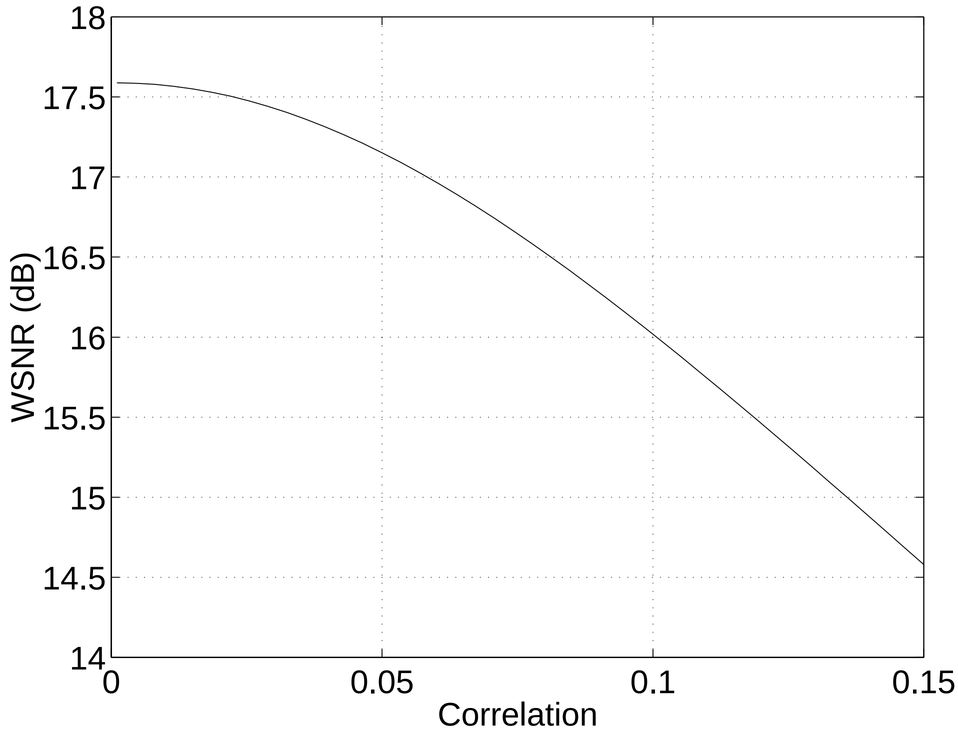
MODELING DISTORTION

- WSNR is a *noise* metric
  - Difference (residual) between original and processed images must be noise
  - Model, compensate for other distortions
  - Measure correlation of residual and original; for accuracy, $C_{RI} < 0.020$



WSNR vs. CORRELATION

- WSNR increasingly inaccurate as correlation increases

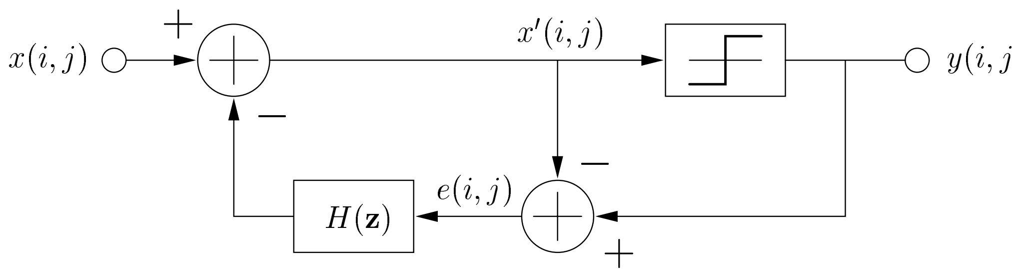


OUTLINE

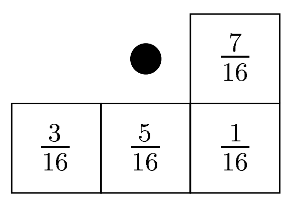
- Introduction to halftoning
- Visual quality metrics for forward and inverse halftoning
  - Human visual system
  - Weighted noise metric (WSNR)
  - Modeling other distortions
- Halftoning by error diffusion
  - Linear gain model
  - Modified error diffusion
  - Noise metric
  - Tonality metric
- Inverse halftoning
  - Algorithm design and results
  - Modeling inverse halftoning
  - Quality metrics
- Rehalftoning and interpolation
- Contributions

ERROR DIFFUSION

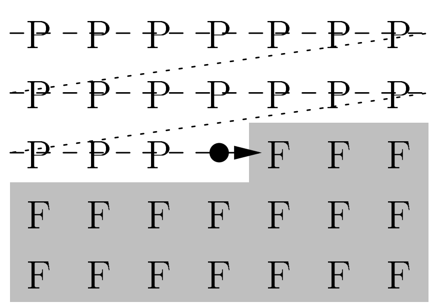
- 2-D delta-sigma modulator
- Noise shaping feedback coder



- Error filter



- Raster scan order



P = Past
F = Future

- Serpentine scan also used

ERROR DIFFUSION (contd.)

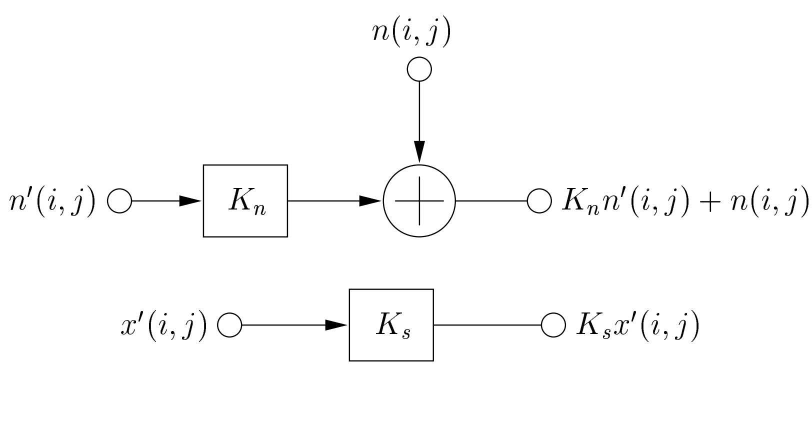
- Quantizer

$$y(i,j) = \begin{cases} 0, & x'(i,j) < 0.5 \\ 1, & x'(i,j) \geq 0.5 \end{cases}$$

- Governing equations

$$\begin{aligned} e(i,j) &= y(i,j) - x'(i,j) \\ x'(i,j) &= x(i,j) - h(i,j) * e(i,j) \end{aligned}$$

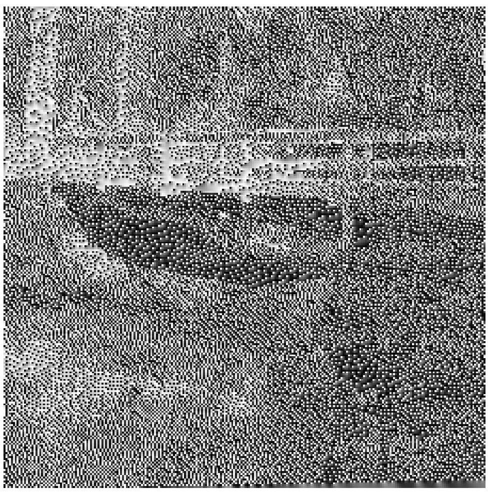
- Non-linearity difficult to analyze
- Linearize quantizer
  [Kite, Evans, Bovik & Sculley 1997]



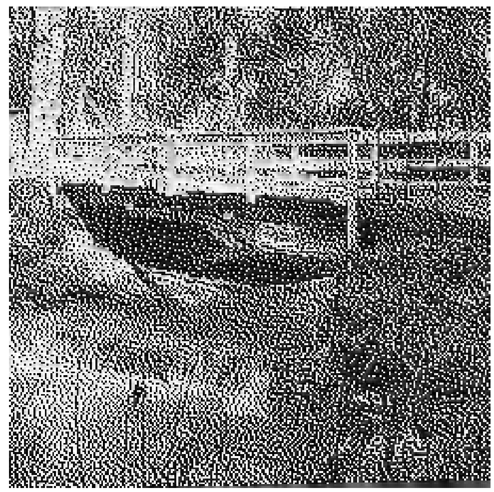
- Separate signal and noise paths
  [Ardalan & Paulos 1987]

LINEAR GAIN MODEL

- Quantization error correlated with input [Knox 1992]



Floyd-Steinberg



Jarvis, Judice & Ninke

- Least squares fit of quantizer input to output defines signal gain

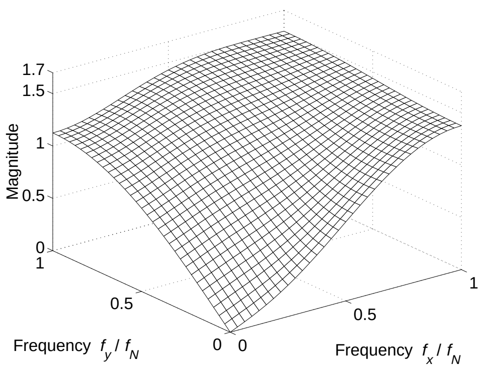
$$K_s = \frac{E[|x'(i,j)|]}{2E[x'(i,j)^2]}$$

- Signal gain: $K_s \approx \text{constant}$
- Noise gain: $K_n = 1$

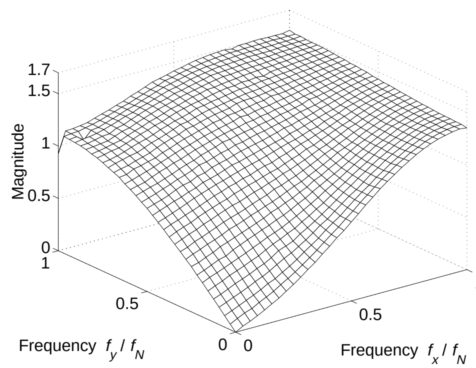
GAIN MODEL PREDICTIONS

- Noise transfer function (NTF)

$$\mathrm{NTF} = 1 - H(\mathbf{z})$$



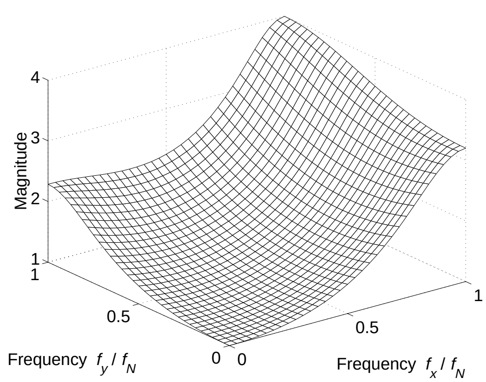
Predicted



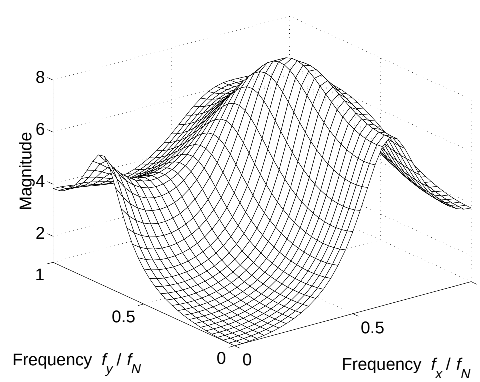
Measured

- Signal transfer function (STF)

$$\mathrm{STF} = \frac{K_s}{1 + (K_s - 1)H(\mathbf{z})}$$



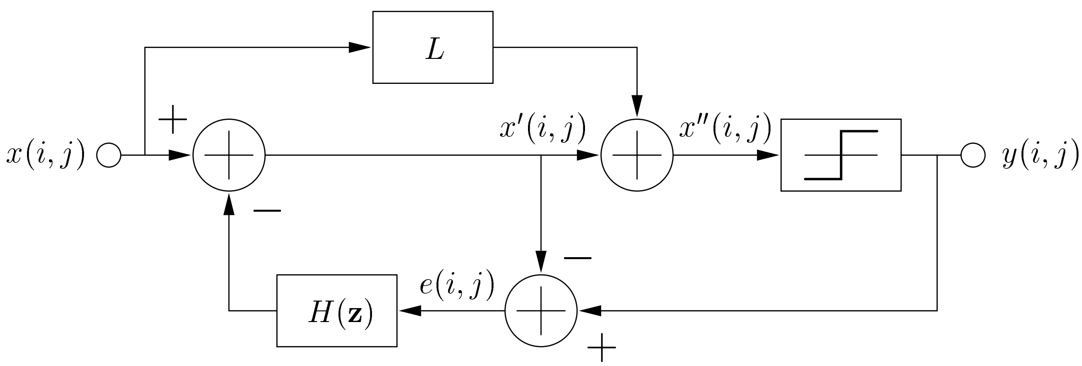
Floyd-Steinberg



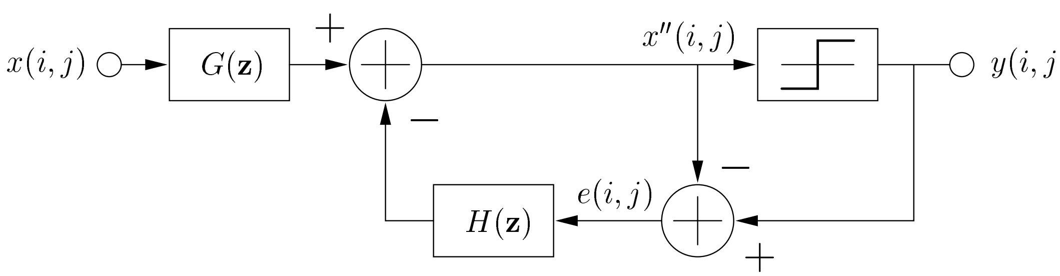
Jarvis *et al.*

MODIFIED ERROR DIFFUSION

- Efficient method of adjusting sharpness [Eschbach & Knox 1991]



- Equivalent circuit: pre-filter

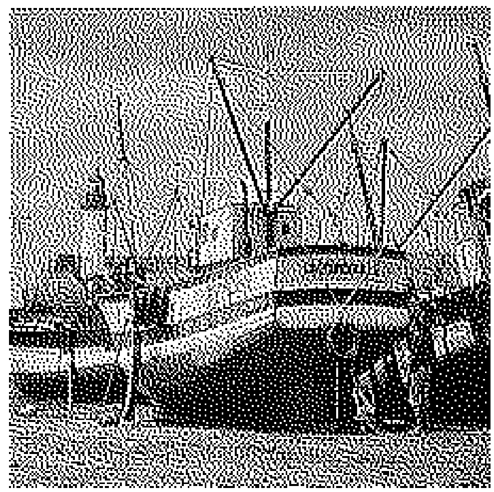


$$G(\mathbf{z}) = 1 + L\,(1 - H(\mathbf{z}))$$

UNSHARPENED HALFTONES

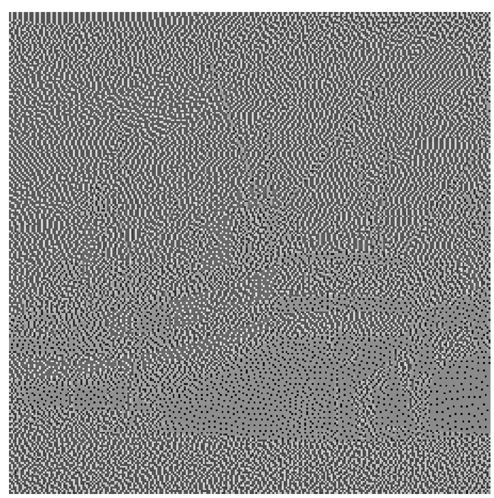
- If $L = \dfrac{1 - K_s}{K_s}$ then $\mathrm{STF} = 1$ (flat)

Original image



Jarvis halftone

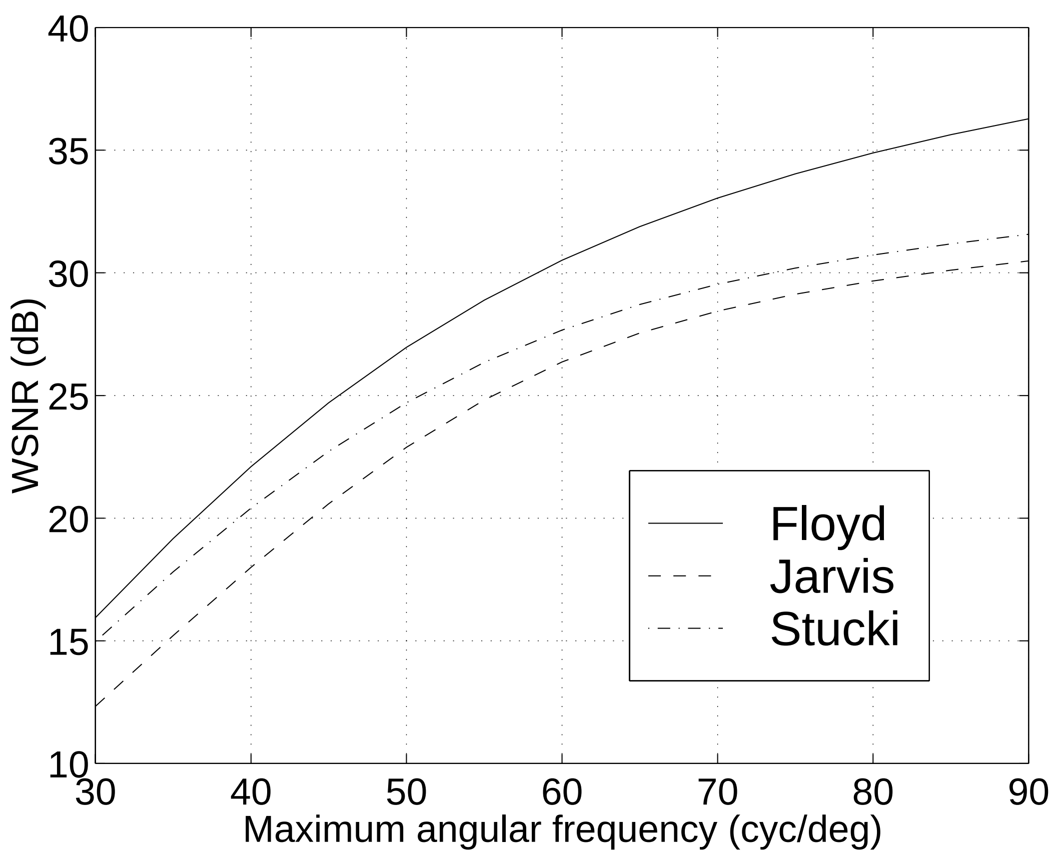
Unsharpened halftone



Residual

OBJECTIVE NOISE METRIC

- To find WSNR
  - Compute signal gain K_s, or use average
  - Generate unsharpened halftone using modified error diffusion
  - Compute WSNR of unsharpened halftone relative to original image



OBJECTIVE TONALITY METRIC

- Limit cycles cause visual ‘worm’ artifacts [Fan & Eschbach 1994]
- Larger filters and serpentine scan result in lower tonality
- Define tonality metric
  - Measure total distortion of sine grating

$$T = \left[\frac{1}{Y(e^{j\omega_f})Y^*(e^{j\omega_f})} \sum_{\omega \in \{\omega_d\}} Y(e^{j\omega})Y^*(e^{j\omega}) \right]^{\frac{1}{2}}$$

  - Average T over grating frequencies
- Agrees with visual results
  - Correct ordering of error filters
  - Serpentine scan less tonal

OUTLINE

- Introduction to halftoning
- Visual quality metrics for forward and inverse halftoning
  - Human visual system
  - Weighted noise metric (WSNR)
  - Modeling other distortions
- Halftoning by error diffusion
  - Linear gain model
  - Modified error diffusion
  - Noise metric
  - Tonality metric
- Inverse halftoning
  - Algorithm design and results
  - Modeling inverse halftoning
  - Quality metrics
- Rehalftoning and interpolation
- Contributions

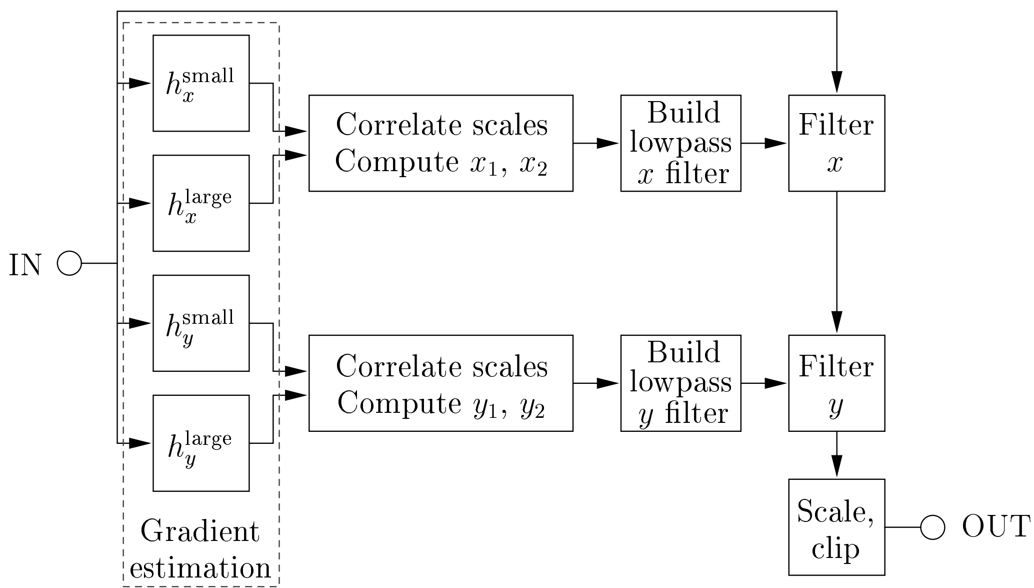
INVERSE HALFTONING

- Attempt to recover grayscale images from halftones
- Applications
  - Digital copiers
  - Scanner software
- Many approaches:
  - Bayesian estimation [Schweizer & Stevenson 1993]
  - Vector quantization [Ting & Riskin 1994]
  - Projection onto convex sets [Hein & Zakhor 1995]
  - Lowpass smoothing and nonlinear filtering [Wong 1995]
  - Wavelet denoising [Xiong, Orchard & Ramchandran 1997]
- Most are iterative and slow
- Best results from wavelet scheme

PROPOSED METHOD

- Apply anisotropic diffusion [Kite, Damera-Venkata, Evans & Bovik 1998]
  - Estimate image gradients
  - Compute diffusion coefficient
  - Smooth within areas, preserve edges
- Unique environment
  - Highpass noise, SNR ≈ 3 dB
  - Tonal
- Solution
  - Specialized gradient estimator
  - Correlate estimate across scales [Mallat & Zhong 1992]
  - Separable—smooth parallel to edges
- Local operations
  - Low memory requirement
  - Low computational cost

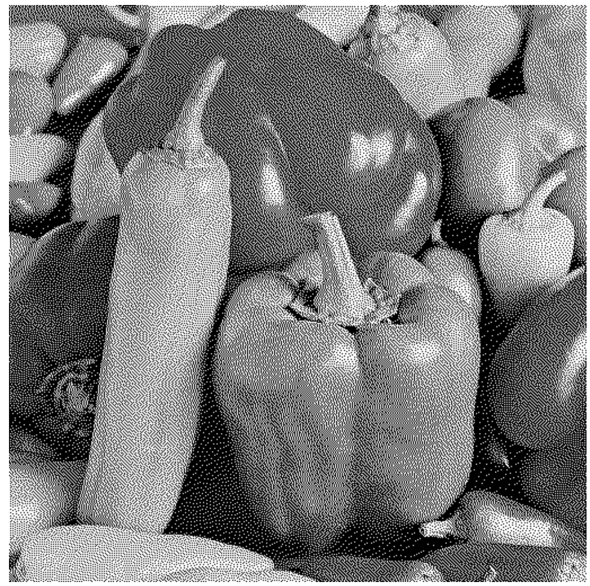
PROPOSED METHOD (contd.)



- Estimate gradients at two scales
  - 7×7, 5×5 FIR filters
  - Integer additions only
- Correlate gradients across scales
  - 5 dB improvement in gradient SNR
- Construct parametric smoother
  - 7×7 separable FIR filter
  - Family optimized for halftones
  - Quantized integer coefficients

INVERSE HALFTONE RESULTS

Original image



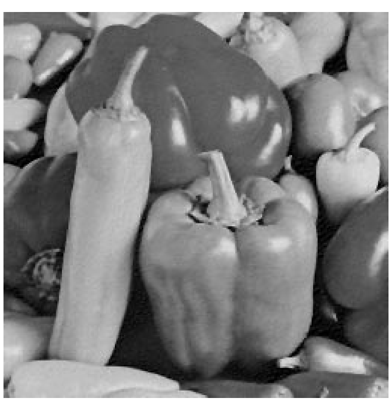
Halftone

Proposed method

Wavelet method

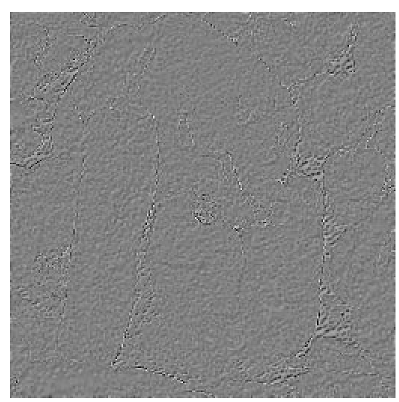
INVERSE HALFTONING MODEL

- Forward/inverse halftoning system blurs image and adds noise
- Model inverse halftoning
  - Compute unsharpened halftone
  - Inverse halftone; save filter parameters at each pixel
  - Filter original image using saved filters
- Typical correlation
  - Inverse halftone: $C_{RI} = 0.32$
  - Model inverse halftone: $C_{RI} = 0.01$



Inverse halftone

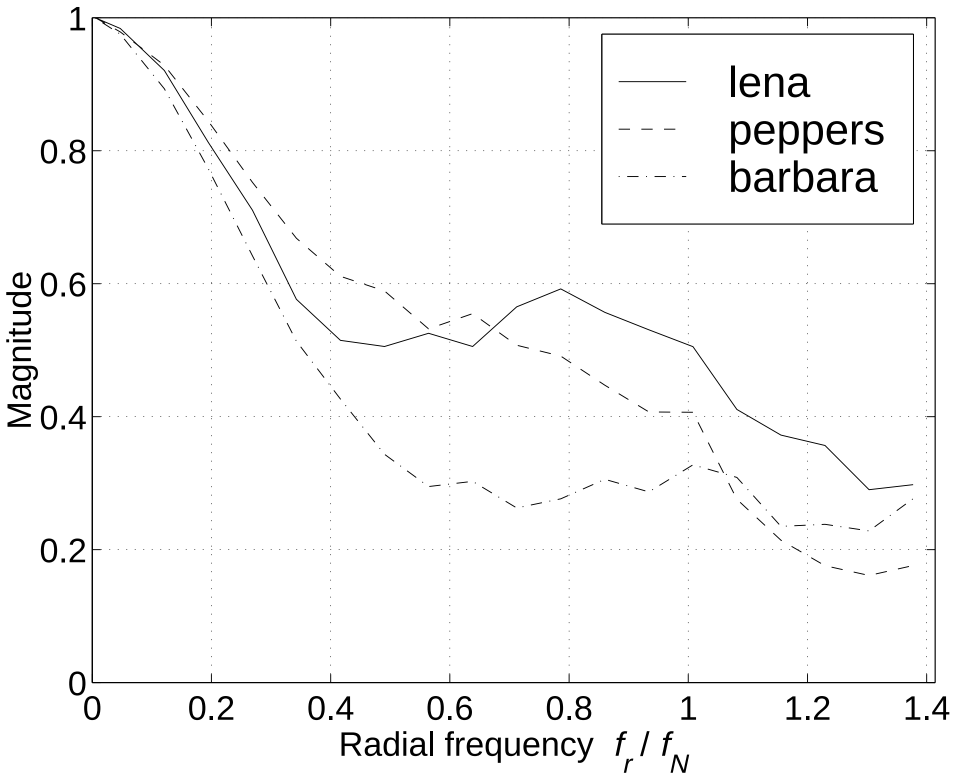
Modeled



Residual (×4)

INVERSE HALFTONE QUALITY

- Compute WSNR
- Compute effective transfer function
  - Divide FFT of model inverse halftone by FFT of original image
  - Radially average over annuli

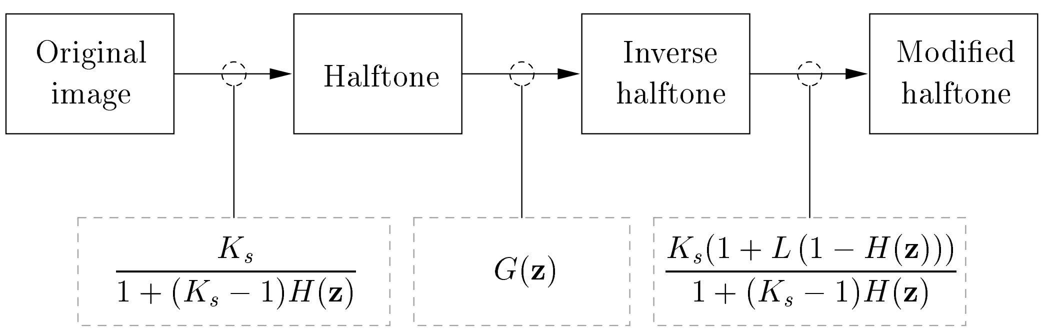


OUTLINE

- Introduction to halftoning
- Visual quality metrics for forward and inverse halftoning
  - Human visual system
  - Weighted noise metric (WSNR)
  - Modeling other distortions
- Halftoning by error diffusion
  - Linear gain model
  - Modified error diffusion
  - Noise metric
  - Tonality metric
- Inverse halftoning
  - Algorithm design and results
  - Modeling inverse halftoning
  - Quality metrics
- Rehalftoning and interpolation
- Contributions

REHALFTONING

- Halftone conversion, manipulation
- Assume input and output are error diffused halftones
- Fixed lowpass inverse halftoning filter, compromise cut-off frequency
  - Noise leakage masked by halftoning
  - Blurring correctable by modified error diffusion
  - Computationally efficient

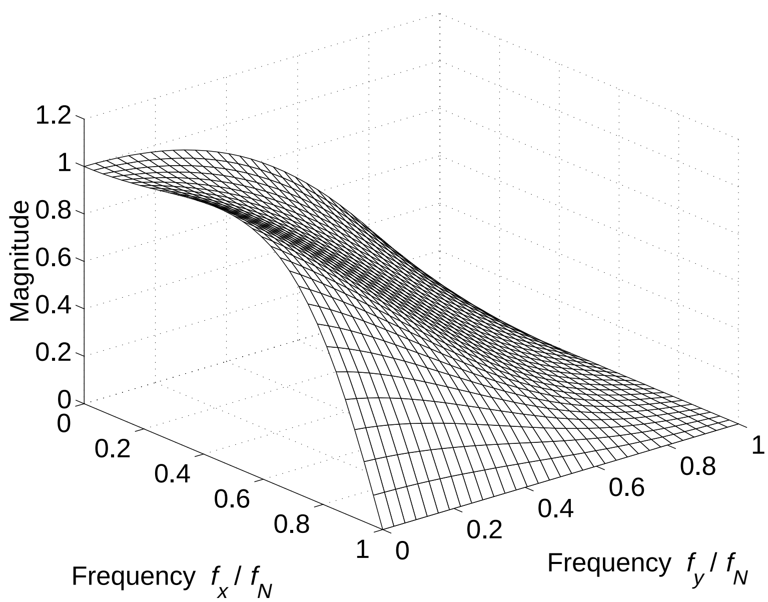


- Use linear gain model to design L for flat response
- Use approximation for digital frequency: $e^{j\omega} \approx 1 + j\omega - \omega^2/2$

REHALFTONING RESULTS

Original image

Rehalftone



Signal transfer function

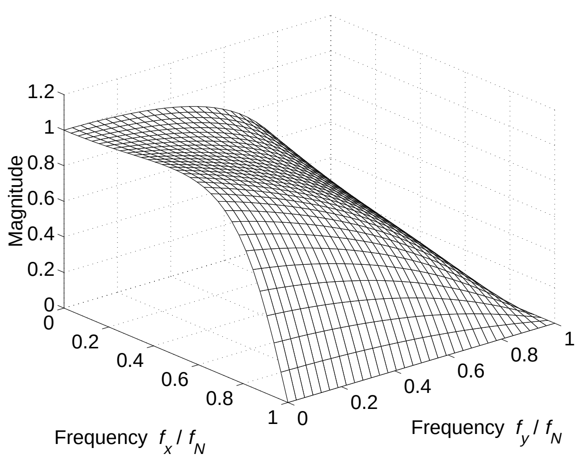
INTERPOLATION

- Image resizing
- Different methods (increasing cost)
  - Nearest neighbor
  - Bilinear
  - Bicubic, cubic splines, lowpass filtering
- Nearest neighbor, bilinear methods
  - Low computational cost
  - Artifacts masked by quantization noise in halftone
  - Blurring correctable by modified error diffusion
- Examine $\times 2$ interpolation; method applies to any scaling factor
- Design L for flat transfer function using linear gain model
- L constant for given interpolation scheme

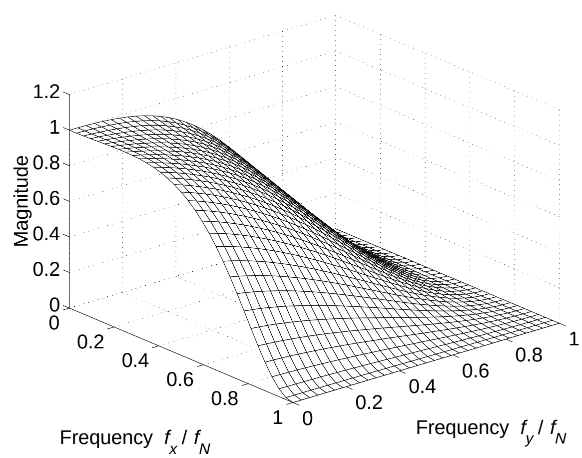
INTERPOLATION RESULTS

Nearest neighbor ×2

Bilinear ×2



Transfer function
L = –0.0105



Transfer function
L = 0.340

CONTRIBUTIONS

- Visual quality metrics for forward and inverse halftones
  - Restriction on correlation for accuracy of WSNR metric
- Linear gain model of error diffusion
  - Accuracy of model established
  - Tonality metric for artifacts
  - Link between filter gain and signal gain
- Inverse halftoning
  - New efficient method, suitable for hardware and embedded software
  - Model for inverse halftoning
  - Quality metrics for inverse halftones
- Rehalftoning and interpolation
  - Efficient algorithms
  - Verifies validity of linear gain model