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BCA Honours | Semester VI | BCA6EJ303(1)

Advanced Digital Image Processing and Computer Vision

Module 2 Comprehensive Notes

Module 2: Frequency Domain Filtering and Image Restoration

Frequency domain analysis decomposes images into spatial sinusoidal frequency components using the Fourier Transform, facilitating frequency filtering and mathematical image restoration.

2.1 The Two-Dimensional Discrete Fourier Transform (2D DFT)

For an M
$\times N$ digital image $f(x,y)$, the 2D DFT is defined by:

$$F(u,v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) e^{-j2pi\left(\frac{ux}{M}+\frac{vy}{N}\right)}$$

Where: *F(u, v)* represents complex frequency coefficients in the 2D spatial frequency plane.

The Inverse DFT reconstructs the spatial image:

$$f(x,y) = \frac{1}{MN} \sum_{u=0}^{M-1} \sum_{v=0}^{N-1} F(u,v) e^{j2pi\left(\frac{ux}{M}+\frac{vy}{N}\right)}$$

Properties of 2D DFT: Separability (2D DFT computed as sequential 1D DFTs along rows then columns), Translation and Rotation, Conjugate Symmetry ($F(u,v) = F^*(-u,-v)$), and the **Convolution Theorem**: spatial convolution $f(x,y) * h(x,y)$ corresponds to point-by-point frequency multiplication $F(u,v)$
$\cdot H(u,v)$.

2.2 Frequency Domain Filter Transfer Functions

Filtering in the frequency domain multiplies centered Fourier transform $F(u,v)$ by filter transfer function $H(u,v)$:

- **Ideal Lowpass Filter (ILPF):** $H(u,v) = 1$ if $D(u,v)$
  $\leq D_0$, and 0 otherwise. Sharp cutoff causes pronounced ringing artifacts in the spatial domain due to the sinc function.
- **Butterworth Lowpass Filter (BLPF):** Smooth transition function with order n:

$$H(u,v) = \frac{1}{1 + [D(u,v)/D_0]^{2n}}$$

- **Gaussian Lowpass Filter (GLPF):** $H(u,v) = e^{-D^2(u,v)/(2D_0^2)}$. Completely eliminates spatial ringing because the Fourier transform of a Gaussian is another Gaussian.
- **Highpass Filters (IHPF, BHPF, GHPF):** Attenuate low-frequency components, emphasizing sharp edges: $H_{\text{HP}}(u,v) = 1 - H_{\text{LP}}(u,v)$.

2.3 Image Degradation and Restoration Models

Image restoration models degradation as an operator H coupled with additive noise $\eta(x,y)$: $g(x,y) = h(x,y) * f(x,y) + \eta(x,y)$, or in frequency space: $G(u,v) = H(u,v)F(u,v) + N(u,v)$.

Restoration Filters

- **Direct Inverse Filtering:** $\hat{F}(u,v) = \frac{G(u,v)}{H(u,v)} = F(u,v) + \frac{N(u,v)}{H(u,v)}$. If $H(u,v)$ approaches zero, noise term $N(u,v)/H(u,v)$ dominates and destroys the reconstruction.
- **Wiener Filtering (Minimum Mean Square Error):** Balances inverse degradation against noise power spectrum:

$$\hat{F}(u,v) = \left[\frac{H^*(u,v)}{|H(u,v)|^2 + \frac{S_\eta(u,v)}{S_f(u,v)}}\right] G(u,v) = \left[\frac{H^*(u,v)}{|H(u,v)|^2 + K}\right] G(u,v)$$

Where: $S_\eta(u,v)$ and $S_f(u,v)$ are noise and signal power spectral densities, and K is a noise-to-signal ratio constant.

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1. Architectural Trade-offs and Computational Complexity

Software architects and systems engineers designing scalable computational pipelines centered on Advanced Digital Image Processing and Computer Vision must methodically navigate core trade-offs:

- **Time Complexity Optimization versus Spatial Footprint:** In high-throughput algorithmic pipelines handling Module 2 Core Concepts and Methods, pre-computing intermediate lookup tables, spatial indices, and hashing structures achieves near-instantaneous $O(1)$ query latency, but inflates the physical memory footprint. Conversely, in-place algorithms minimize RAM utilization at the cost of higher CPU cycle counts. Modern architectures dynamically calibrate memory allocations using memory-mapped files and cache-aware structures.
- **Concurrency Scalability versus Thread Contention:** While multi-core hardware allows horizontal execution, concurrent modifications to shared state structures create severe lock contention, thread synchronization bottlenecks, and cache line invalidation storms. High-performance frameworks deploy lock-free algorithms, optimistic concurrency control, and atomic compare-and-swap (CAS) primitives.

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- **Algorithmic Determinism versus Heuristic Scalability:** Exact mathematical algorithms frequently encounter NP-hard combinatorial barriers as problem dimensions scale. Contemporary systems bridge this gap by deploying bounded approximation algorithms and meta-heuristics that produce near-optimal solutions within guaranteed execution time windows.

2. Empirical Comparative Framework

A structured comparative assessment clarifies operational distinctions across conventional paradigms and modern production implementations in Advanced Digital Image Processing and Computer Vision:

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