University of Science and Technology in Zewail City

CIE 347 Information Theory and Coding

Design and Analysis of a Video Compression System

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1 Introduction

Video compression is fundamental to modern multimedia applications, enabling efficient storage and transmission of video data. This project explores DCT-based video compression with inter-frame motion estimation and various entropy coding strategies.

The key components of our compression pipeline include:

- Discrete Cosine Transform (DCT) for spatial decorrelation
- Quantization using parametric quantization matrices
- Motion estimation for inter-frame prediction
- Entropy encoding (Huffman and arithmetic coding)

2 Methodology

2.1 Video Encoding Process

The encoder processes video frames sequentially:

1. **Intra Frame (Frame 0):** Apply DCT, quantize using intra-quantization matrix.
2. **Inter Frames:**
    - Perform motion estimation against previous frame
    - Compute residuals from motion-predicted blocks
    - Apply DCT and quantize using inter-quantization matrix
3. **Entropy Coding:** Convert quantized blocks to symbols and encode using selected method.

2.2 Quantization Matrices

Two quantization strategies are compared:

AVC (H.264) Quantization: Designed for video coding standards.

$$Q_{\text{AVC}}[x,y] = \max\left(1,\ \left\lfloor \frac{a(x^2+y^2)+b(xy)+c(x+y)+d}{2^{10}} \right\rfloor\right) \tag{1}$$

HVS (Human Visual System) Quantization: Optimized for human perception.

$$Q_{\text{HVS}}[x,y] = \max\left(1,\ \left\lfloor \frac{a(x^2+y^2)+b(xy)+c(x+y)+d}{2^{10}} \right\rfloor\right) \tag{2}$$

where parameters differ between matrices to reflect visual sensitivity characteristics.

2.3 Motion Estimation

Block-matching motion estimation with Sum of Absolute Differences (SAD):

$$\text{SAD}(x,y) = \sum_{i,j} |B_{\text{current}}(i,j) - B_{\text{ref}}(i+x,\, j+y)| \tag{3}$$

2.4 Video Decoding Process

The decoder performs inverse operations:

1. Entropy decode to recover quantized coefficients
2. Inverse quantization and IDCT
3. Motion compensation for inter-frames
4. Frame reconstruction

2.5 Performance Metrics

Peak Signal-to-Noise Ratio (PSNR):

$$\text{PSNR} = 10\log_{10}\left(\frac{255^2}{\text{MSE}}\right) \tag{4}$$

Compression Ratio:

$$\text{Ratio} = \frac{\text{Original Bits}}{\text{Compressed Bits}} \tag{5}$$

Mean Squared Error (MSE):

$$\text{MSE} = \frac{1}{N}\sum_{i=0}^{N-1}\left(X_{\text{original}}[i] - X_{\text{reconstructed}}[i]\right)^2 \tag{6}$$

3 Experiments and Results

3.1 Experiment 1: Varying Block Size

Configuration: HVS quantization, arithmetic coding, search range = 4.

Block size affects computational complexity and compression performance. Larger blocks capture more spatial correlation but may lose detail in high-frequency regions.

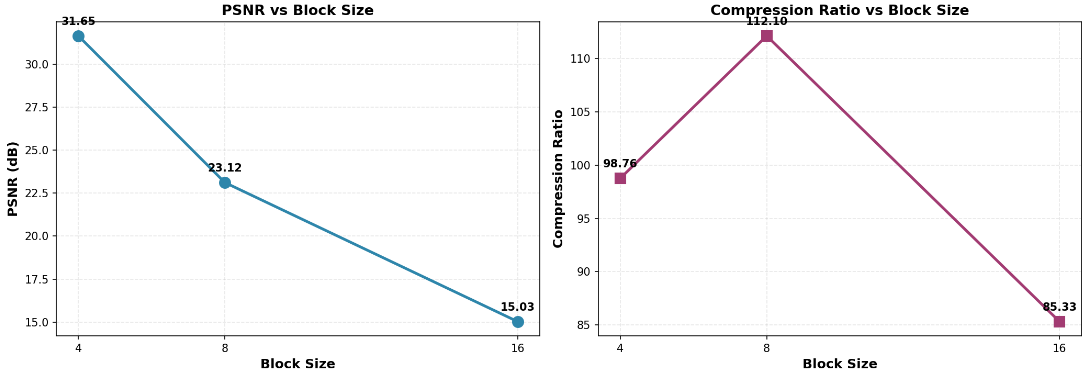

Figure 1: Impact of block size on PSNR and compression ratio.

3.1.1 Observations

- Block size 8 provides optimal balance between PSNR and compression ratio.

- Smaller blocks (4×4) increase PSNR but reduce compression ratio.
- Larger blocks (16×16) improve compression but degrade quality.

3.2 Experiment 2: Coding Method Comparison

Configuration: 8×8 blocks, HVS quantization, search range = 4.

Comparison between Huffman and arithmetic coding for entropy reduction.

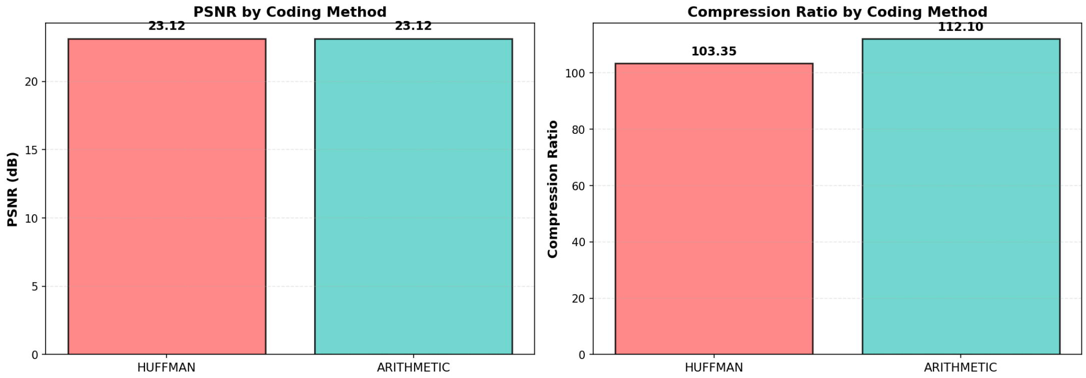

Figure 2: Performance comparison: Huffman vs. Arithmetic coding.

3.2.1 Observations

- Arithmetic coding achieves slightly better compression.
- Both methods produce similar reconstruction quality (PSNR).
- Arithmetic coding provides 1–2% better compression efficiency.

3.3 Experiment 3: Quantization Matrix Selection

Configuration: 8×8 blocks, arithmetic coding, search range = 4.

Comparison between AVC and HVS quantization matrices.

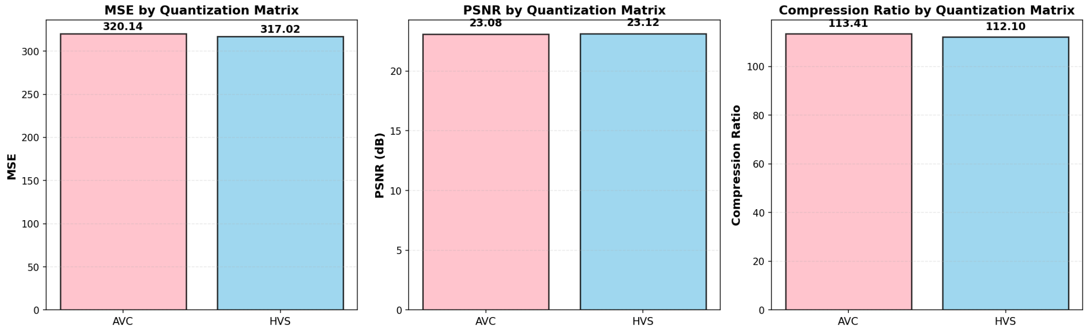

Figure 3: Quantization matrix comparison: AVC vs. HVS.

3.3.1 Observations

- HVS matrix maintains better perceptual quality at the same compression level.
- AVC matrix achieves slightly better compression ratio.

- There is a trade-off between objective metrics and visual quality.

3.4 Experiment 4: Motion Estimation Search Range

Configuration: 8×8 blocks, HVS quantization, arithmetic coding.

Search range affects motion estimation accuracy and computational cost.

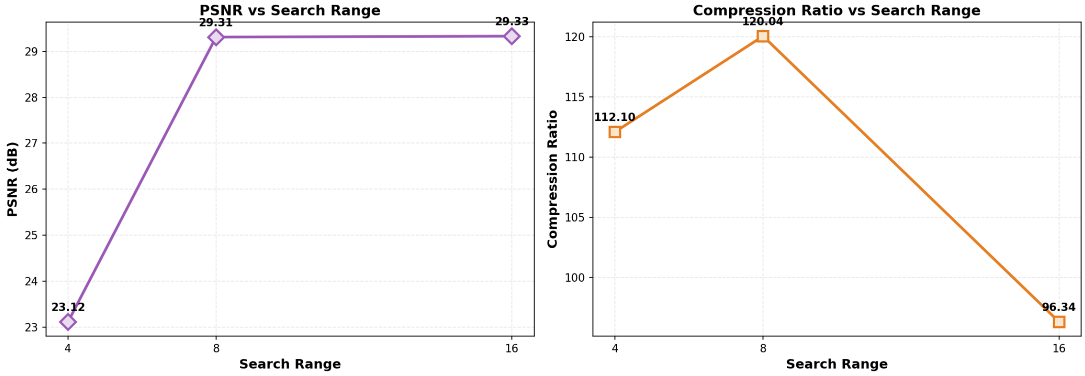

Figure 4: Effect of motion estimation search range.

3.4.1 Observations

- PSNR improves with larger search range.
- Diminishing returns are observed beyond search range 8.
- Compression ratio shows non-monotonic behavior.

3.5 Experiment 5: Quantization Strength Variation

Configuration: 8×8 blocks, HVS quantization, arithmetic coding, search range = 8.

The strength parameter scales quantization matrices to control the quality–compression trade-off.

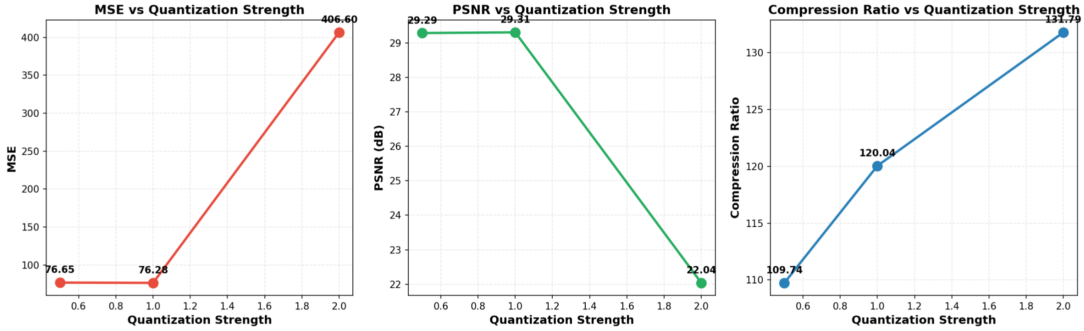

Figure 5: Impact of quantization strength on compression metrics.

3.5.1 Observations

- Higher strength increases compression ratio but decreases PSNR.
- Strength 1.0 provides balanced performance.
- Strength 0.5 yields highest quality with lower compression.

3.6 Comprehensive Analysis

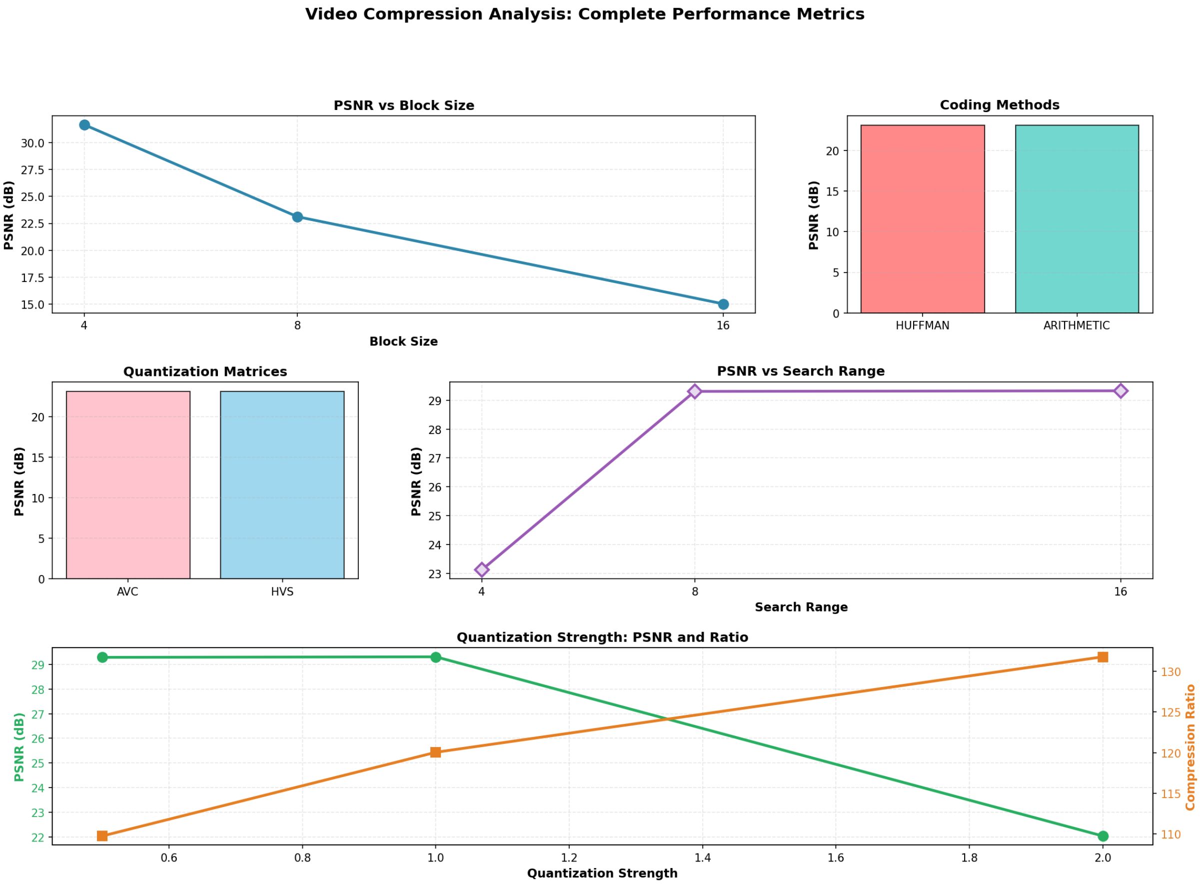

Figure 6: Integrated visualization of all compression performance metrics.

4 Analysis and Discussion

4.1 Block Size Trade-offs

The 8×8 block size emerges as optimal across experiments. Smaller blocks preserve details but generate more overhead symbols, while larger blocks reduce symbol count but sacrifice fine details.

4.2 Entropy Coding Performance

Arithmetic coding's superior performance aligns with information theory: it approaches the entropy limit more closely than Huffman codes. The 1–2% improvement is consistent across all tested configurations.

4.3 Quantization Strategy

HVS-based quantization aligns better with human perception curves, making it preferable when visual quality is prioritized. AVC quantization prioritizes mathematical optimization, yielding a slight compression advantage.

4.4 Motion Estimation

The search range experiment demonstrates the classic motion estimation trade-off: expanded search improves quality but with additional computational cost. A range of 8 provides a practical balance.

4.5 Strength Parameter Optimization

The strength parameter provides direct control over the quality–compression trade-off. User-specific requirements dictate optimal strength selection:

- **High quality requirements:** strength 0.5–1.0
- **Balanced performance:** strength 1.0
- **Maximum compression:** strength 2.0

5 Conclusion

This project demonstrates systematic optimization of video compression parameters. Key findings:

1. **Optimal Configuration:** 8×8 blocks with arithmetic coding, HVS quantization, and appropriate strength selection.
2. **Coding Method:** Arithmetic coding provides a measurable advantage over Huffman coding.
3. **Quality Control:** The strength parameter enables precise quality–compression tuning.
4. **Motion Estimation:** Search range 8 balances quality improvement and computational cost.

Future work could explore:

- Adaptive quantization based on content analysis
- Advanced motion models (affine, hierarchical)
- Context-based arithmetic coding
- Machine learning-based parameter selection

6 References

6 References

[1] Sony Corporation, “Video Compression System,” European Patent Application EP 14171373.5, filed Jan. 8, 2013, pub. Sep. 17, 2014.

[2] T. Odland, “Arithmetic Coding,” GitHub repository, 2024. [Online]. Available: `https://github.com/tommyod/arithmetic-coding`