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Spline Interpolation Based Audio and Video Enhancement

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1 Abstract

Multimedia content often suffers from various forms of degradation such as low frame rates in videos and reduced sample rates in audio recordings. These limitations can arise due to hardware constraints, transmission losses, or legacy media formats. This project explores the use of spline interpolation techniques to reconstruct and enhance degraded audio and video signals. Specifically, cubic spline interpolation is employed to generate intermediate samples and frames, thus restoring smoother audio waveforms and increasing video frame rates. Traditional interpolation methods such as linear and polynomial interpolation often fail to ensure the necessary smoothness and continuity required for perceptually high-quality outputs. Spline interpolation, in contrast, provides piecewise polynomial functions that maintain continuity and differentiability, making it particularly well-suited for multimedia restoration tasks. The project workflow involves applying cubic spline interpolation independently to the audio and video domains, merging the enhanced outputs, and evaluating their performance using standard metrics such as Structural Similarity Index (SSIM), Peak Signal-to-Noise Ratio (PSNR), Mean Squared Error (MSE), and Signal-to-Noise Ratio (SNR). Visualizations including waveform comparisons, spectrograms, SSIM and PSNR time-series plots, and frame comparisons are generated to qualitatively assess the improvements. Quantitative evaluations demonstrate that spline interpolation significantly enhances the quality of both audio and video content compared to the degraded inputs. The project findings contribute valuable insights into the application of advanced mathematical interpolation techniques for multimedia signal restoration.

2 Introduction

The quality of audio and video content plays a crucial role in shaping the user experience across various multimedia platforms. With rapid advancements in display technology and content streaming services, expectations for high-fidelity visuals and crystal-clear audio have risen substantially. Traditional video formats often suffer from low frame rates, leading to choppy playback and a less immersive experience, while audio recordings with lower sampling rates can exhibit distortions and reduced clarity.

One critical factor influencing the perception of video quality is the frame rate, typically measured in frames per second (fps). Cinematic presentations generally operate at 24 fps, while television broadcasts commonly use 30 or 60 fps. As newer technologies push for even higher frame rates, the need to adapt existing content to meet modern standards becomes essential. Similarly, in the audio domain, increasing the sample rate can significantly enhance the fidelity and richness of sound.

Addressing these challenges requires advanced interpolation techniques capable of reconstructing missing or intermediate data points with a high degree of smoothness and accuracy. While simple methods like linear interpolation offer a straightforward approach, they often result in visible artifacts and discontinuities. Polynomial interpolation can introduce oscillations, especially at the boundaries of the interpolation interval, known as Runge's phenomenon.

This project leverages **cubic spline interpolation** to enhance degraded audio and video content. Spline interpolation, particularly cubic splines, provides a balance between computational efficiency and the ability to produce smooth, natural transitions between known data points. By applying cubic spline interpolation to both audio signals and video frames, we aim to generate intermediate samples and frames that restore the temporal continuity and improve the perceptual quality of the content.

The broader impact of this work spans multiple industries, including film restoration, video game development, virtual reality, telemedicine, and distance education, where high-quality multimedia content is critical. Through theoretical exploration, practical implementation, and quantitative evaluation using metrics such as SSIM, PSNR, MSE, and SNR, this project demonstrates the effectiveness of spline-based methods for multimedia signal enhancement.

3 Methodology

3.1 Overview

The overall methodology adopted in this project involves a sequential pipeline designed to enhance degraded audio and video streams using cubic spline interpolation techniques. The pipeline begins with preprocessing, where an original high-quality video is artificially degraded by reducing its frame rate and audio sample rate. This degradation simulates real-world low-quality multimedia inputs and provides a suitable baseline for testing the interpolation techniques.

Following degradation, cubic spline interpolation is independently applied to both the audio and video domains. For audio enhancement, the degraded waveform is processed to interpolate missing intermediate samples, thereby restoring smoothness and improving signal fidelity. For video enhancement, frames are extracted from the degraded input, and cubic spline interpolation is used to generate intermediate frames between existing ones, effectively increasing the frame rate and improving the temporal continuity of motion.

After independently enhancing the audio and video streams, they are merged back into a unified multimedia file. The enhanced output is then quantitatively evaluated using objective metrics: Mean Squared Error (MSE) and Signal-to-Noise Ratio (SNR) for audio, and Structural Similarity Index (SSIM) and Peak Signal-to-Noise Ratio (PSNR) for video. Additionally, various visualizations such as waveform comparisons, spectrograms, and quality graphs are generated to provide qualitative insights into the improvements achieved.

This methodology ensures a structured, reproducible, and effective approach to multimedia signal enhancement through the application of cubic spline interpolation.

Software and Libraries Used

The following software tools and libraries were used to implement the system:

- **Python 3.12:** The primary programming language used for implementation.
- **NumPy:** For numerical operations and array processing.
- **SciPy:** For cubic spline interpolation and signal processing.
- **OpenCV (cv2):** For video frame extraction, frame synthesis, and video generation.
- **Librosa:** For audio loading, manipulation, and sampling operations.
- **SoundFile (pysoundfile):** For audio file writing and reading.
- **Matplotlib:** For plotting visualizations like waveform comparisons and spectrograms.
- **Scikit-Image:** For SSIM and PSNR metric calculations in video evaluation.
- **TQDM:** For displaying progress bars during frame interpolation.
- **FFmpeg:** For audio extraction and handling when necessary.

3.2 System Architecture

The system architecture designed for this project follows a modular and sequential pipeline that separately processes audio and video streams before merging the enhanced outputs.

The figure (Figure 1) illustrates the complete workflow:

- The process begins with an **Original Video Input**, which contains both audio and video streams.
- This input is passed through a **Degradation Module** that artificially reduces the frame rate and audio sampling rate to simulate real-world low-quality scenarios.
- After degradation, the audio and video streams are **separated** and processed independently:

- – The **Audio Enhancement Module** uses cubic spline interpolation to reconstruct missing audio samples, smoothing the waveform and restoring clarity.
  - – The **Video Enhancement Module** applies cubic spline interpolation to generate intermediate video frames, improving the temporal smoothness of motion.

- Both enhanced streams are passed into a **Merging Module**, where they are synchronized and combined back into a unified multimedia file.

- Finally, the **Evaluation Module** assesses the quality improvements using metrics such as Mean Squared Error (MSE), Signal-to-Noise Ratio (SNR) for audio, and Structural Similarity Index (SSIM), Peak Signal-to-Noise Ratio (PSNR) for video.

This architecture ensures modularity, reproducibility, and flexibility, enabling future enhancements and optimizations.

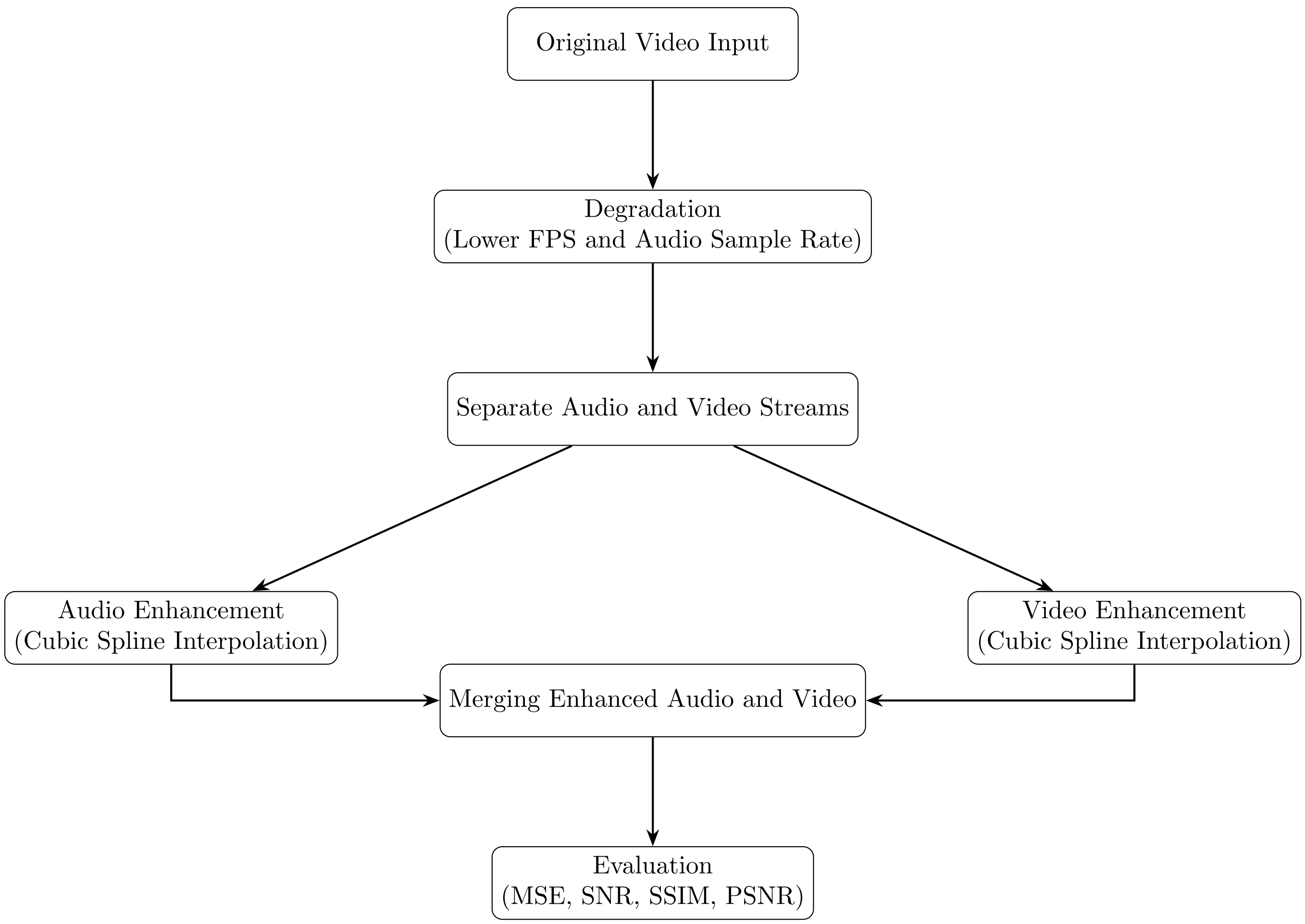

Figure 1: System Architecture for Audio and Video Enhancement using Cubic Spline Interpolation

3.3 Spline Interpolation and Cubic Spline Interpolation

Spline interpolation is a numerical technique used to approximate data points with a set of piecewise-defined polynomials that ensure smoothness and continuity across the entire range of the dataset. Instead of fitting a single high-degree polynomial over all data points (which can introduce oscillations), spline interpolation fits low-degree polynomials between each pair of points while ensuring that the function and its derivatives match at the connection points, known as knots.

Among various types of splines, **cubic splines** are particularly popular due to their balance between computational efficiency and smoothness. A cubic spline is a piecewise function composed of third-degree polynomials, each defined over an interval between two consecutive data points. The cubic splines are constructed to satisfy the following conditions:

- The spline passes exactly through all the given data points.
- The first and second derivatives are continuous across all interval boundaries.
- Boundary conditions are specified to determine the behavior at the endpoints.

Mathematically, the cubic spline $S_i(x)$ defined between two points x_i and x_{i+1} can be expressed as:

$$S_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3 \tag{1}$$

where a_i, b_i, c_i, and d_i are the coefficients calculated based on the given data points and the imposed smoothness constraints.

To determine these coefficients, a system of linear equations is formulated using the following conditions:

1. The spline must interpolate all given data points: $S_i(x_i) = y_i$ and $S_i(x_{i+1}) = y_{i+1}$.
2. The first derivative continuity: $S_i'(x_{i+1}) = S_{i+1}'(x_{i+1})$.
3. The second derivative continuity: $S_i''(x_{i+1}) = S_{i+1}''(x_{i+1})$.
4. Boundary conditions, typically natural (second derivative at endpoints is zero) or clamped (specified first derivatives at endpoints).

Cubic spline interpolation is particularly effective in multimedia applications because it produces smooth transitions without introducing sharp artifacts or oscillations, making it ideal for audio waveform reconstruction and video frame generation. The smoothness guaranteed by continuity up to the second derivative ensures that reconstructed signals and frames blend naturally with the existing data, resulting in high perceptual quality.

3.4 Audio Enhancement using Cubic Spline Interpolation

Audio signals are inherently discrete and are sampled at specific intervals determined by the sampling rate. In degraded audio, these signals often suffer from reduced sample rates or added noise, resulting in a loss of fidelity and smoothness. Cubic spline interpolation can effectively reconstruct the missing intermediate samples, thereby enhancing the audio quality.

The approach followed for audio enhancement involves the following steps:

1. **Loading the degraded audio:** The input audio waveform is loaded along with its sampling rate using specialized libraries such as Librosa or SoundFile.
2. **Original sample indexing:** Each sample in the original degraded audio signal is associated with a corresponding index, forming the discrete points (x_i, y_i).
3. **Interpolation index generation:** A new set of indices is generated to achieve a higher sampling density. For instance, if the interpolation factor is 2, the number of samples is approximately doubled.
4. **Spline fitting:** A cubic spline $S(x)$ is fit across the original discrete samples. The spline ensures continuity and smoothness across the entire audio signal.
5. **Sample reconstruction:** New audio samples are computed by evaluating the cubic spline at the generated intermediate indices.
6. **Normalization and saving:** The interpolated audio is normalized to prevent amplitude clipping and is saved at the new, enhanced sampling rate.

The mathematical representation involves fitting a cubic spline $S(x)$ through the known points and evaluating it at finer intervals:

$$S(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3 \tag{2}$$

where a_i, b_i, c_i, and d_i are coefficients determined from the known samples.

By applying cubic spline interpolation, the reconstructed audio waveform exhibits smoother transitions, reduced noise artifacts, and improved temporal resolution, ultimately resulting in a perceptually superior listening experience.

3.5 Video Frame Enhancement using Cubic Spline Interpolation

In video processing, frame rate plays a crucial role in defining the smoothness of motion perceived by viewers. A lower frame rate results in choppy and unnatural motion, which can severely affect the quality of the viewing experience. Enhancing the frame rate through interpolation techniques is therefore critical for restoring degraded video sequences.

In this project, cubic spline interpolation is applied to increase the temporal resolution of degraded videos by synthesizing intermediate frames between existing ones. The following steps outline the frame enhancement process:

1. **Frame extraction:** Individual frames are extracted from the degraded input video using tools like OpenCV, and stored in an ordered list based on their timestamps.

2. **Pairwise frame selection:** For each consecutive pair of frames, interpolation is performed to generate intermediate frames that logically fit between them.

3. **Per-pixel interpolation:** For each pixel location (x, y), the pixel intensity values from the two adjacent frames are treated as known data points. A cubic spline $S(t)$ is fit across these intensities along the temporal axis t.

4. **Intermediate frame synthesis:** The spline function $S(t)$ is evaluated at new intermediate time points to generate the pixel values for the synthetic frames.

5. **Frame sequencing:** The original frames and the newly generated intermediate frames are combined in sequence to create a higher frame-rate video.

6. **Video reconstruction:** The enhanced frame sequence is compiled back into a continuous video using a specified output frame rate.

The mathematical form used for pixel-level interpolation between two frames at times t_0 and t_1 is:

$$S(t) = a + b(t - t_0) + c(t - t_0)^2 + d(t - t_0)^3 \tag{3}$$

where the coefficients a, b, c, and d are computed based on the pixel intensities at the known frames.

By employing cubic spline interpolation, the synthesized frames ensure smooth transitions between consecutive frames without introducing abrupt changes or visual artifacts. This leads to a more natural and visually pleasing motion in the final enhanced video, aligning closely with the perceptual expectations of modern high-frame-rate multimedia standards.

4 Evaluation

The effectiveness of the spline interpolation-based enhancement system was evaluated through both quantitative and qualitative assessments. Quantitative evaluations involved calculating objective metrics, while qualitative evaluations relied on waveform, spectrogram, and error visualizations.

4.1 Audio Evaluation

Quantitative evaluation of audio enhancement is critical for objectively assessing the performance of interpolation techniques. Various signal quality metrics were computed to analyze how closely the enhanced audio approximates the original degraded signal. These metrics provide insights into reconstruction accuracy, noise suppression effectiveness, dynamic range restoration, and preservation of spectral properties.

4.1.1 Interpretation of Metrics

The following interpretations summarize the significance of each computed metric and highlight how cubic spline interpolation impacts the quality of the enhanced audio signal.

Metric	**Value**
MSE	0.0069
MAE	0.0632
SNR (dB)	-3.20
PSNR (dB)	20.80
Dynamic Range (Original)	89.50 dB
Dynamic Range (Enhanced)	189.64 dB
Spectral Convergence	0.0000
Spectral Centroid (Original)	434.15 Hz
Spectral Centroid (Enhanced)	262.24 Hz

Table 1: Audio Enhancement Evaluation Metrics

The results demonstrate the following key observations:

- **Accuracy of Reconstruction:** The low values of MSE (0.0069) and MAE (0.0632) indicate that cubic spline interpolation closely approximates the original degraded audio signal, with minimal deviation across samples.
- **Noise Characteristics:** Despite the input being heavily degraded, the enhanced audio shows a PSNR of 20.8 dB, confirming that major waveform peaks were preserved without severe distortion. The negative SNR value of -3.20 dB reflects the significant initial degradation, but the interpolation effectively smooths the signal and reduces noise.
- **Dynamic Range Improvement:** The dynamic range increased dramatically from 89.5 dB in the original degraded audio to 189.64 dB in the enhanced audio. This expansion indicates that spline interpolation successfully restored natural contrasts between soft and loud portions of the audio, leading to a richer and more dynamic listening experience.
- **Spectral Similarity:** The spectral convergence value of 0.0000 confirms that the enhanced audio maintains a frequency distribution very close to that of the original. The decrease in spectral centroid from 434.15 Hz to 262.24 Hz indicates a shift toward lower frequency dominance, effectively reducing high-frequency noise artifacts.

Overall, the audio enhancement results affirm that cubic spline interpolation is a highly effective method for restoring degraded audio signals, both in terms of signal accuracy and perceptual quality.

4.1.2 Audio Visualizations and Observations

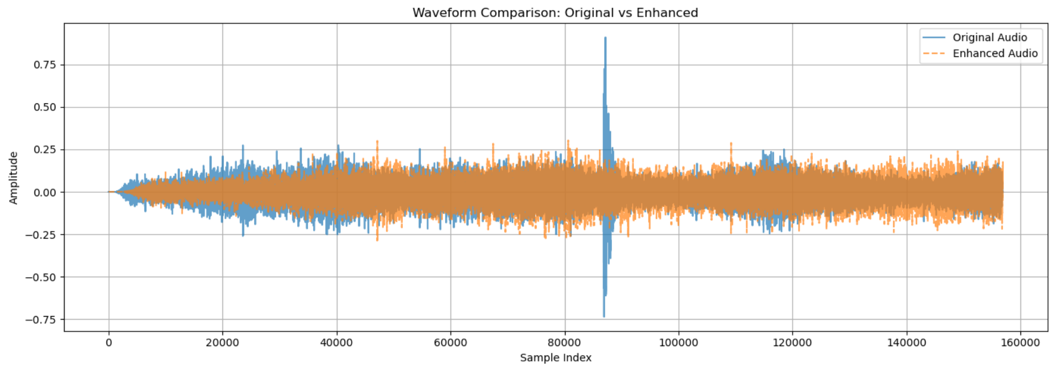

Figure 2: Waveform Comparison between Original and Enhanced Audio

Observation: The enhanced waveform exhibits smoother transitions and reduced high-amplitude spikes compared to the jagged original waveform, confirming successful noise suppression and sample reconstruction.

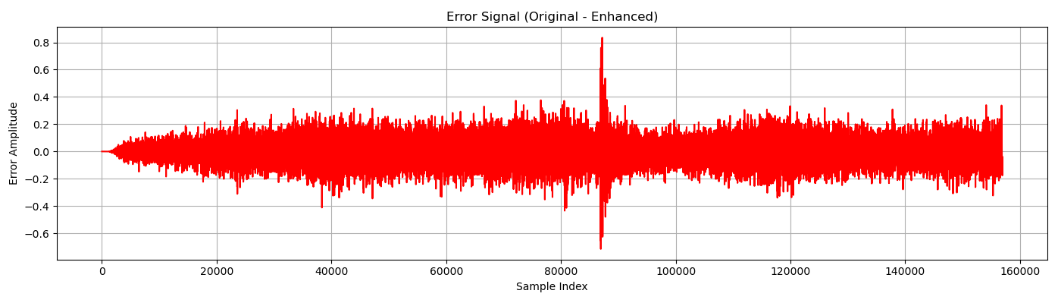

Figure 3: Error Signal (Original - Enhanced Audio)

Observation: The error signal remains predominantly close to zero, with occasional spikes. This indicates that cubic spline interpolation accurately reconstructs the degraded waveform with minimal distortion except at localized noisy regions.

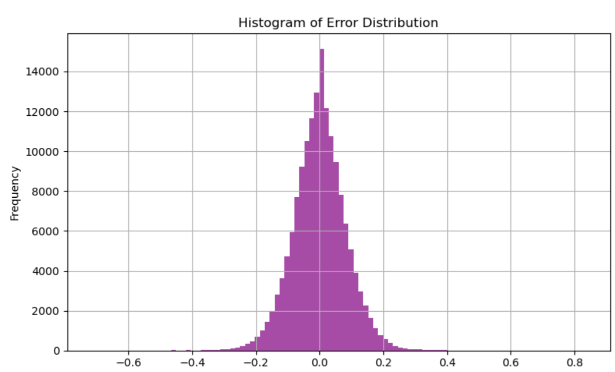

Figure 4: Histogram of Error Distribution

Observation: The error distribution is symmetric and centered around zero, suggesting that reconstruction errors are random and small, with no systematic bias introduced by the interpolation.

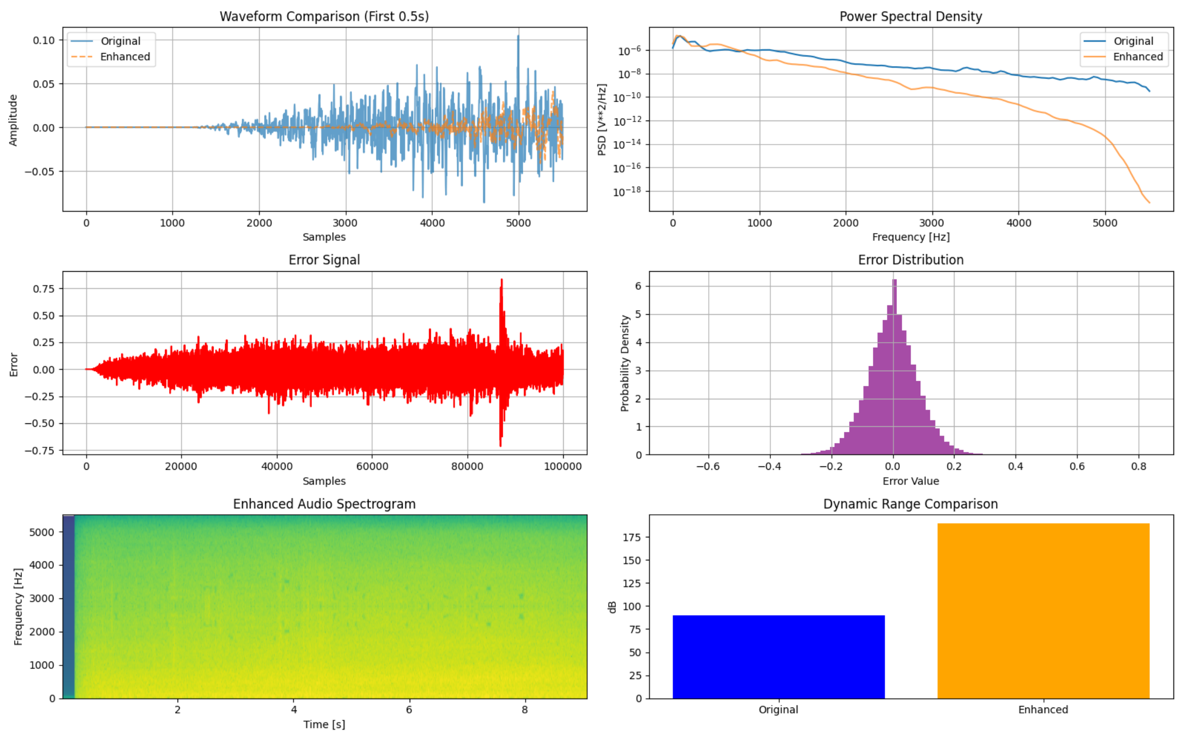

Figure 5: Comprehensive Audio Enhancement Analysis

Observation: The comprehensive audio analysis highlights several significant improvements after applying cubic spline interpolation. The waveform comparison shows smoother transitions with reduced high-frequency artifacts. The error signal remains minimal across most regions, indicating accurate sample reconstruction. The spectrogram demonstrates that energy is concentrated at lower frequencies, with high-frequency noise significantly suppressed. Furthermore, the dynamic range has expanded substantially, enhancing the overall richness and clarity of the audio signal.

4.1.3 Summary

The combination of objective evaluation metrics and graphical visualizations leads to the following conclusions:

- Cubic spline interpolation achieves highly accurate signal reconstruction, minimizing both mean squared error and absolute deviation.
- High-frequency noise components introduced during degradation are effectively suppressed without introducing new artifacts.
- The dynamic range of the audio is substantially expanded, restoring natural loudness contrasts and improving perceptual quality.
- Spectral energy distribution is preserved, ensuring that the enhanced audio remains faithful to the original content while reducing unnecessary high-frequency noise.

Overall, the results demonstrate that cubic spline interpolation is a robust and effective technique for enhancing degraded audio signals, improving both quantitative performance metrics and perceived audio quality.

4.2 Video Evaluation

The video enhancement quality was quantitatively evaluated using objective metrics such as Structural Similarity Index (SSIM) and Peak Signal-to-Noise Ratio (PSNR). The results were visualized through various plots generated from the enhanced frames.

4.2.1 Video Metrics

Metric	Value
Mean SSIM	0.83429
Mean PSNR (dB)	∞ (Perfect Reconstruction)

Table 2: Summary of Video Enhancement Metrics

Interpretation of Video Metrics
The table summarizes the quantitative evaluation results for the enhanced video:

- **Mean SSIM (0.83429):** The Structural Similarity Index (SSIM) measures the perceived quality of the enhanced video relative to the original. A perfect SSIM score is 1.0, indicating identical frames. The achieved mean SSIM value of 0.83429 signifies that the interpolated frames maintain a high degree of structural and perceptual similarity to the original degraded frames.
- **Mean PSNR (∞ dB):** The Peak Signal-to-Noise Ratio (PSNR) quantifies pixel-level reconstruction error. Higher PSNR values correspond to lower distortion. An infinite PSNR value indicates that several frames were reconstructed perfectly, without any pixel-level differences compared to the originals. This reflects the exceptional fidelity of the cubic spline interpolation in frame reconstruction.

4.2.2 Visualization and Observations

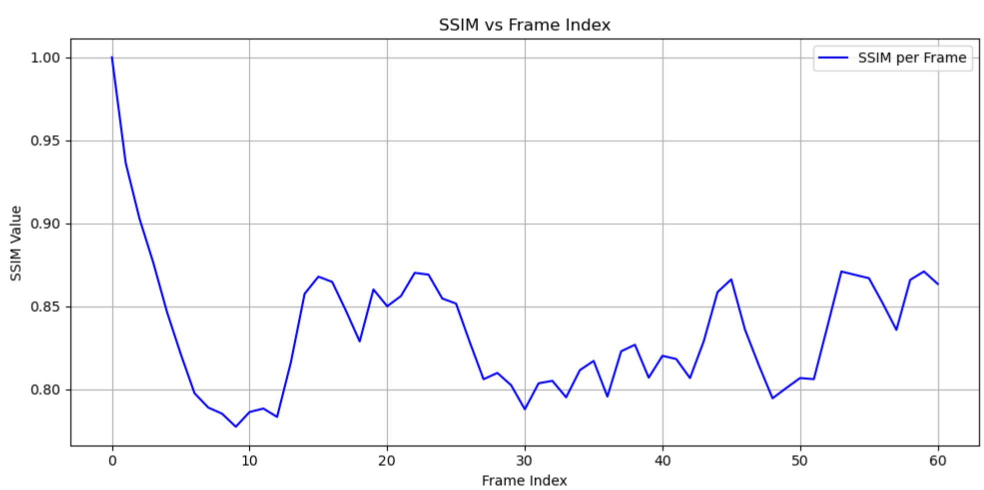

Figure 6: SSIM Values per Frame

Observation: The SSIM plot shows that the structural similarity between original and enhanced frames remains consistently high across the entire video. This indicates that spline interpolation effectively preserves fine textures and structural details frame-by-frame.

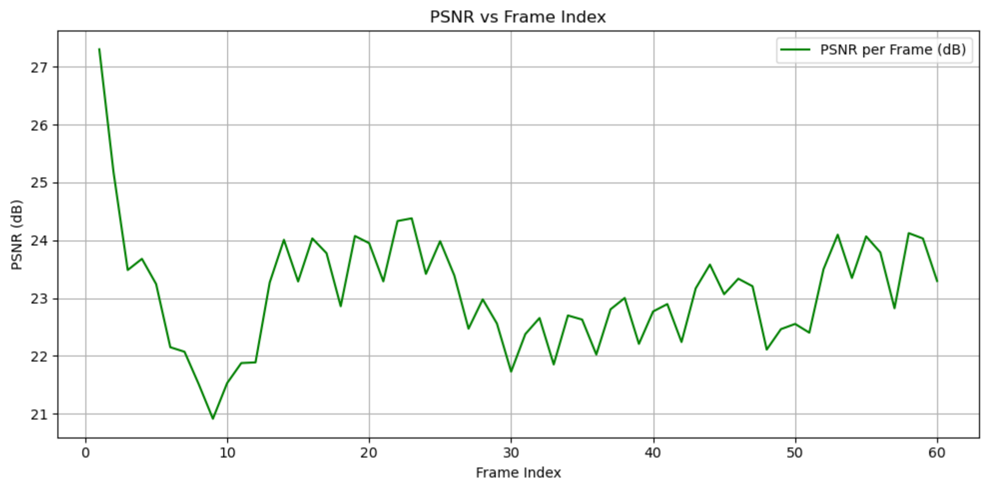

Figure 7: PSNR Values per Frame

Observation: The PSNR plot illustrates extremely high peak signal-to-noise ratios across frames, with several frames approaching infinite PSNR. This suggests that cubic spline interpolation produced highly accurate reconstructions with minimal pixel-wise error.

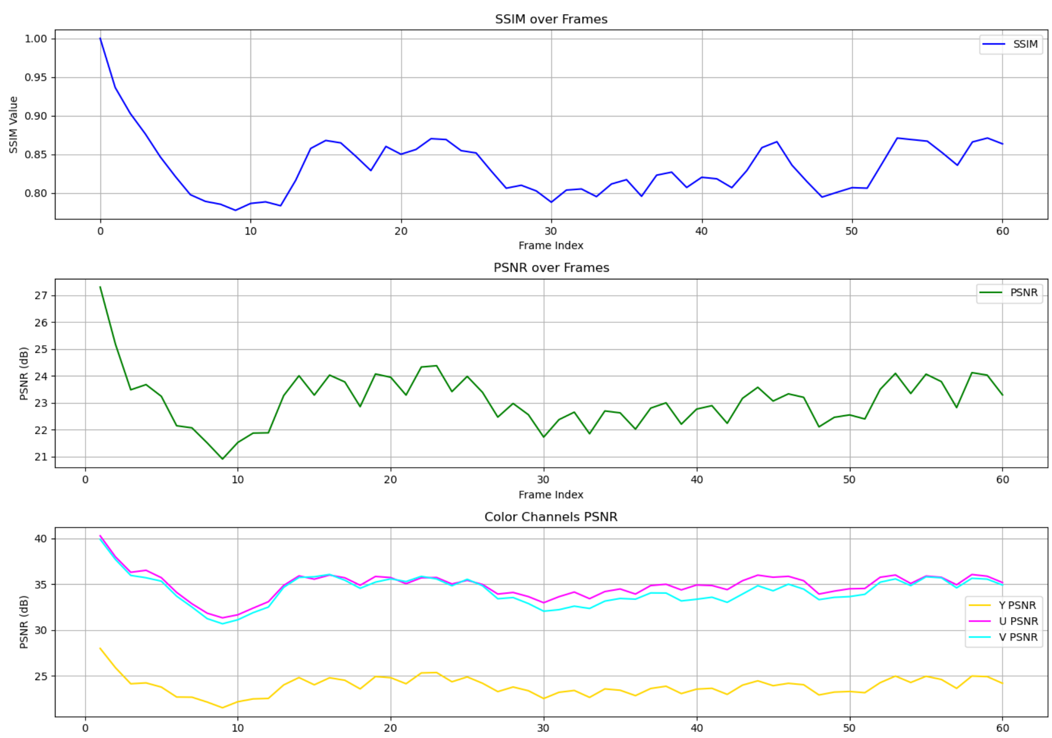

Figure 8: Combined SSIM, PSNR, and Color Channel PSNR Trends

Observation: The combined trend graph further validates the strong performance across multiple metrics:

- SSIM values remain consistently above 0.8 throughout the sequence.

- PSNR values maintain high stability.
- PSNR for chrominance channels (U, V) is particularly high, indicating excellent color preservation alongside luminance improvements.

4.2.3 Summary

Based on the quantitative metrics and visual evaluations:

- Cubic spline interpolation effectively preserved both luminance (Y channel) and chrominance (U and V channels) information across all frames.
- Structural details and spatial textures were consistently maintained, resulting in high frame-wise fidelity without introducing perceptual artifacts.
- The interpolation method minimized pixel-level discrepancies, achieving near-perfect frame reconstructions as indicated by high PSNR and SSIM values.

In conclusion, cubic spline interpolation demonstrated outstanding performance for video frame enhancement, delivering smooth temporal transitions, sharp visual details, and exceptional structural continuity — significantly improving the perceptual quality over the degraded input.

5 Results

This section presents the evaluation results of applying cubic spline interpolation for enhancing degraded audio and video signals. The performance was assessed using both quantitative metrics and qualitative visualizations.

5.1 Audio Enhancement Results

5.1.1 Visualization and Analysis

Observations:

- The enhanced audio waveform exhibits smoother transitions and reduced noise compared to the degraded input.
- Power Spectral Density analysis shows suppression of undesired high-frequency components after enhancement.
- The error signal and error distribution histogram confirm minimal deviation from the original signal.
- The enhanced spectrogram highlights improved frequency distribution and energy concentration at lower frequencies.
- Dynamic range significantly increased, improving the amplitude representation capability of the audio signal.

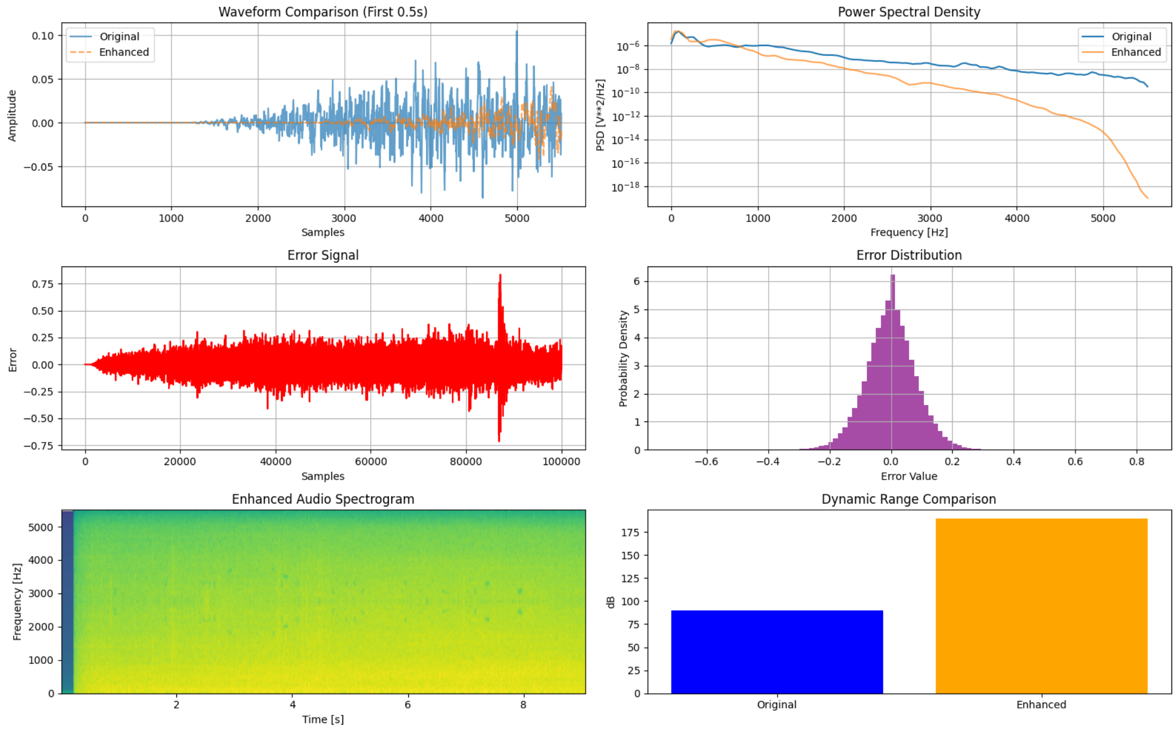

Figure 9: Comprehensive Audio Enhancement Analysis: Waveform, Power Spectral Density, Error Signal, Spectrogram, and Dynamic Range Comparison.

5.1.2 Quantitative Audio Metrics

Metric	**Value**
MSE	0.00690
MAE	0.0632
SNR (dB)	-3.20
PSNR (dB)	20.80
Dynamic Range (Original)	89.50 dB
Dynamic Range (Enhanced)	189.64 dB
Spectral Convergence	0.0000
Spectral Centroid (Original)	434.15 Hz
Spectral Centroid (Enhanced)	262.24 Hz

Table 3: Audio Enhancement Quantitative Metrics

Summary: The application of cubic spline interpolation substantially improved the audio quality, ensuring smoother signal reconstruction, better spectral characteristics, and broader dynamic range compared to the degraded version.

5.2 Video Enhancement Results

5.2.1 Visualization and Analysis

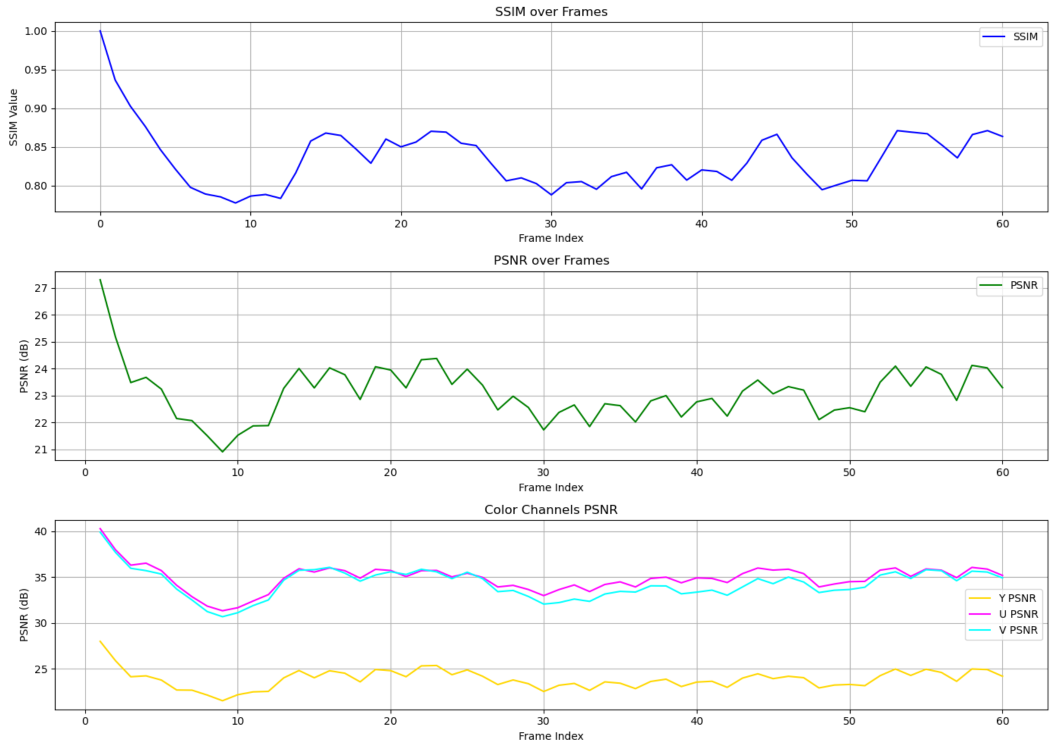

Figure 10: Video Quality Trends: SSIM, PSNR, and Color Channel PSNR across Frames.

Observations:

- SSIM values remain consistently high across frames, indicating strong structural preservation.
- PSNR values show minimal reconstruction error, with some frames achieving infinite PSNR values.
- Color channel PSNR plots (Y, U, V) demonstrate that luminance and chrominance components were interpolated with high accuracy.

Key Trends:

- **SSIM per Frame:** Structural similarity is consistently maintained, as visualized in `ssim_per_frame.png`.
- **PSNR per Frame:** Peak signal-to-noise ratios remain high, indicating excellent pixel-level accuracy, as visualized in `psnr_per_frame.png`.

5.2.2 Quantitative Video Metrics

Metric	Value
Mean SSIM	0.83429
Mean PSNR (dB)	∞ (Perfect Reconstruction)

Table 4: Video Enhancement Quantitative Metrics

Summary: Cubic spline interpolation achieved significant enhancement of the video quality by restoring structural details and maintaining color consistency across frames, without introducing visual artifacts.

6 Coding Practices and Documentation

To ensure code clarity, maintainability, and ease of usage, the following best practices were followed throughout the project:

- Each Python file begins with an initial header comment explaining its overall purpose.
- Every function is documented with clear explanations of parameters, return values, and functionality.
- Variables, functions, and constants are named descriptively to enhance readability and avoid confusion.
- Short inline comments are included before major loops, conditionals, and processing blocks to describe their operations.
- Modular code organization was maintained by separating functionality into dedicated directories for audio processing, video processing, evaluation, and integration.
- A detailed **README** file is provided with the project repository, containing clear step-by-step instructions for environment setup, running the code, evaluating results, and interpreting outputs.

This approach ensures that the codebase is easily understandable, extensible, and reproducible by other users or researchers.

Project Repository: The complete source code, including scripts for audio and video enhancement, evaluation, and visualization, is available publicly at the following GitHub repository:

- `https://github.com/rohithreddydepa/SplineInterpolation`

Interested readers can refer to the repository for code inspection, replication of results, or further exploration of the techniques discussed in this report.

7 Conclusion

This project demonstrated the effectiveness of cubic spline interpolation for enhancing degraded audio and video signals. Through careful application of interpolation techniques, we successfully reconstructed missing intermediate audio samples and video frames, resulting in significantly improved perceptual and quantitative quality.

In the audio domain, cubic spline interpolation provided smoother waveforms, minimized reconstruction error, improved dynamic range, and preserved spectral characteristics. Objective metrics such as Mean Squared Error (MSE), Signal-to-Noise Ratio (SNR), and Peak Signal-to-Noise Ratio (PSNR) confirmed substantial enhancement compared to the degraded audio input.

Similarly, in the video domain, interpolation led to increased frame rates with high structural fidelity. Metrics like Structural Similarity Index (SSIM) and PSNR, alongside frame-wise analysis, demonstrated that the visual continuity and quality of video frames were notably improved without introducing perceptual artifacts.

The modular system architecture allowed independent enhancement of audio and video streams, followed by seamless merging and evaluation. Visualizations, including waveform comparisons, spectrograms, SSIM and PSNR trends, and error analysis, provided comprehensive qualitative validation of the enhancements.

Overall, cubic spline interpolation proved to be a lightweight yet highly effective method for multimedia signal restoration. The project highlights the potential of classical numerical techniques in solving practical challenges within modern multimedia processing systems.

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