A Major Project on

Human Face Restoration using GFP-GAN

A Report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Technology

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Year 2023-2024

DECLARATION

We hereby declare that the Report entitled **Human Face Restoration using GFP-GAN** submitted for the award of Bachelor of Technology Degree is our original work and the Report has not formed the basis for the award of any degree, diploma, associate ship or fellowship of similar other titles. It has not been submitted to any other University or Institution for the award of any degree or diploma.

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CERTIFICATE

This is to certify that the Report entitled **Human Face Restoration using GFP-GAN** that is being submitted by **Ms. Anakam Gayatri** bearing Hall Ticket number **20EG105602, Mr. Palamoni Akhil** bearing Hall Ticket number **20EG105704,** and **Ms. Kandula Sathwika** bearing Hall Ticket number **20EG105622** in partial fulfillment for the award of **Bachelor of Technology** in **Computer Science and Engineering** to the **Anurag University** is a record of Bonafide work carried out by them under my guidance and supervision.

The results embodied in this Report have not been submitted to any other University or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENT

We would like to express our sincere thanks and deep sense of gratitude to the project supervisor **Dr. P. Nagaraj** for his constant encouragement and inspiring guidance without which this project could not have been completed. His critical reviews and constructive comments improved our grasp of the subject and steered us to the fruitful completion of the work. His patience, guidance, and encouragement made this project possible.

We would like to express our special thanks to **Dr. V. Vijaya Kumar**, Dean School of Engineering, Anurag University, for their encouragement and timely support of our B. Tech program.

We would like to acknowledge our sincere gratitude for the support extended by **Dr. G. Vishnu Murthy**, Dean, Dept. of CSE, Anurag University. We also express our deep sense of gratitude to **Dr. V.V.S.S.S Balaram**, Academic coordinator, **Dr. Pallam Ravi**, Project in-Charge, **Dr. A Jyothi**, Project Co-Ordinator and Project review committee members, whose research expertise and commitment to the highest standards continuously motivated us during the crucial stage our project work.

ABSTRACT

Traditional video restoration techniques often prioritize wide ranging improvements like noise reduction and colour correction. This can leave crucial facial details, essential for conveying character and emotion, less well-defined. The Human Face Restoration Project addresses this challenge by leveraging GFPGAN, a deep learning algorithm specifically designed for facial enhancement in the video.

Our approach involves extracting individual video frames, precisely applying GFPGAN to enhance facial features, and then seamlessly reconstructing the video using MoviePy. This frame-by-frame method ensures consistent restoration and avoids the inconsistencies common to other techniques. Importantly, the original audio track is preserved for perfect audio-visual synchronization. Additionally, the project incorporates Streamlit to provide an intuitive user interface for easy video input, restoration customization, and output viewing.

The Human Face Restoration Project offers a significant advancement in human facial characteristics in the video restoration. It holds immense potential for applications in film restoration, archival preservation, and enhancing the impact of modern video content where the nuanced details of facial expression are paramount.

Keywords: video restoration, facial enhancement, GFPGAN, deep learning, MoviePy, Streamlit, film restoration, archival preservation

LIST OF FIGURES

LIST OF TABLES

INDEX

1. INTRODUCTION

Traditional video restoration techniques offer impressive improvements in noise reduction, colour correction, and upscaling. However, they often neglect a crucial aspect of visual storytelling – the clarity and expressiveness of human faces. Blurry facial features, lack of definition, and unnatural smoothing remain persistent issues, hindering the full potential of video restoration.

This is where the "Human Face Restoration using GFP-GAN" project steps in. This innovative solution leverages the power of GFPGAN, a specialized deep learning model, to target facial features specifically in video. By analysing and enhancing each face frame-by-frame of the video, the project ensures consistent and hyper-realistic detail revival. Unlike conventional methods, this GFP-GAN-powered approach delivers sharp, authentic facial features, injecting new life into historical footage, personal videos, and even materials used in forensic analysis.

1.1 Problem Statement

The widespread availability of digital video recording devices has led to a vast collection of personal and historical video footage. Unfortunately, much of this footage suffers from degradation due to factors like:

- **Low-Resolution Recording:** Early recording technologies or limitations in storage capacity might have resulted in videos with low resolution, leading to blurry and indistinct facial features.
- **Compression Artifacts:** Video compression techniques can introduce artifacts like blurring or blocking, further obscuring facial details and reducing the visual quality of the footage.
- **Degradation over Time:** Videotapes and other storage formats can deteriorate over time, causing color fading, noise artifacts, and further loss of detail, especially in facial features.

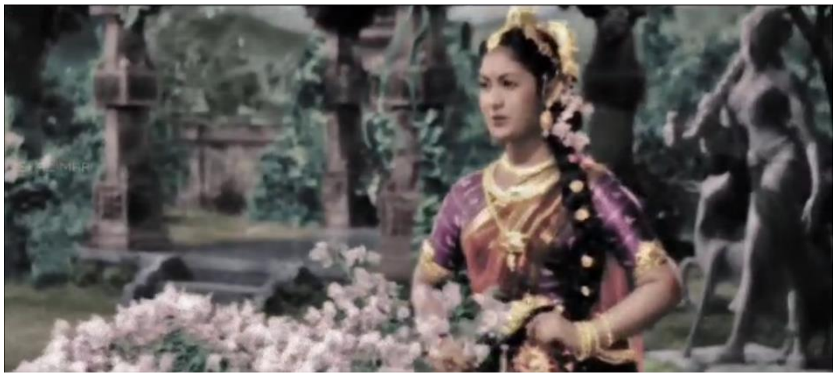


Figure 1 Old movie clip with a blurry face.

These limitations significantly hinder the viewing experience and make it difficult to:

- **Clearly identify individuals:** Blurry or low-resolution faces make it challenging to recognize people within the video footage, limiting its usefulness for tasks like historical record-keeping, event documentation, or personal video archives.
- **Extract meaningful details:** Facial expressions and subtle details crucial for understanding the content of a video are often lost due to blurry features. This can hinder the emotional impact of the footage and limit its potential for analysis.
- **Enjoy the visual quality:** Low-resolution and blurry videos offer a diminished viewing experience, making it less engaging and enjoyable to watch.

1.2 Need of Technology

The need for your video restoration project with GFP-GAN stems from the ever-growing presence of video in our lives and the challenges associated with preserving and enhancing visual quality over time. Here's a breakdown of the key needs your technology addresses:

- **Limitations of Generic Techniques:** Conventional restoration tools don't fully address the unique complexities of the human face. They lack the targeted focus necessary to restore intricate details with natural-looking results.
- **Prioritizing the Face:** GFP-GAN's core strength lies in its hyper-focus on facial features, unlike generic techniques that treat every part of the image with equal importance. This leads to restorations that are far more believable and accurate.

- **Understanding Facial Structure:** The magic of GFP-GAN lies in its understanding of the underlying structure of human faces. Because of this, it can reconstruct damaged or missing elements (like eyes obscured by reflection) with a high degree of authenticity.
- **Preserving Identity:** A key challenge in face restoration is maintaining the identity of the person in the image. GFP-GAN excels at this, ensuring that the restored face remains recognizable, not just generic.
- **Consistency Across Video:** When applied to video footage, GFP-GAN ensures a consistent appearance of faces across frames, preventing jarring changes in how a person looks from one moment to the next. This is crucial when restoring archival or historical footage.
- **Enhancing Video Conferencing:** Low-resolution webcams and bandwidth limitations can lead to blurry or pixelated video feeds during video conferencing. Your technology has the potential to improve facial clarity and overall video quality, leading to a more natural and engaging communication experience.

2. LITERATURE SURVEY

Video restoration encompasses various techniques aimed at improving the visual quality of degraded videos. These degradations can arise from factors such as low-resolution recording formats, compression artifacts, noise, or physical damage to the video source. Traditional video restoration methods often employ techniques like filtering, interpolation, and deblocking to address these issues [1]. However, these methods may struggle with significant degradation, particularly when dealing with specific aspects of the video content like blurry facial features.

Recent advancements in deep learning, particularly the emergence of Generative Adversarial Networks (GANs), have opened new avenues for video restoration. GANs are a class of deep learning models consisting of two competing neural networks: a generator and a discriminator. The generator learns to create new data instances that resemble the real data distribution, while the discriminator attempts to distinguish between real and generated data [2]. This adversarial training process allows GANs to capture complex patterns and generate high-fidelity outputs.

Several studies have explored the application of GANs for video restoration tasks. [3] proposes a recurrent GAN architecture for video super-resolution, achieving significant improvements in terms of peak signal-to-noise ratio and visual quality. [4] presents a temporally consistent video inpainting framework using GANs, effectively handling missing or corrupted regions within videos. These studies demonstrate the potential of GANs for general video quality enhancement.

While existing research explores GANs for overall video restoration, our work focuses on targeted facial enhancement within videos. Generative Facial Prior Guided Networks (GFP-GANs) represent a specific type of GAN architecture designed for facial restoration in images. [5] introduces GFP-GAN, demonstrating its effectiveness in restoring blurry or aged faces while preserving other facial details. [6] builds upon this work by incorporating a novel perceptual loss function, further improving the quality of restored facial images. These studies establish GFP-GAN as a powerful tool for facial restoration tasks.

3. PROPOSED METHOD

3.1 Existing System

The existing video restoration techniques are remarkable in addressing challenges such as noise reduction and upscaling, significantly enhancing overall video quality. However, a limitation can be noted as these methods often fall short in preserving and enhancing crucial facial details, resulting in a final output that appears blurry and unnatural. This drawback motivates a need for a targeted solution focused specifically on facial feature enhancement within videos.

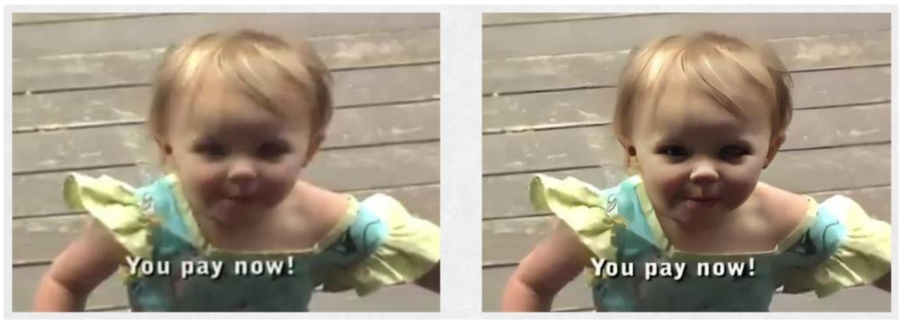


Figure 3.1 Problem Illustration 1

Standard restoration techniques often rely on heavy blurring or filtering to reduce imperfections. But this tends to erase subtle but vital details like skin texture, fine lines, and delicate facial features.

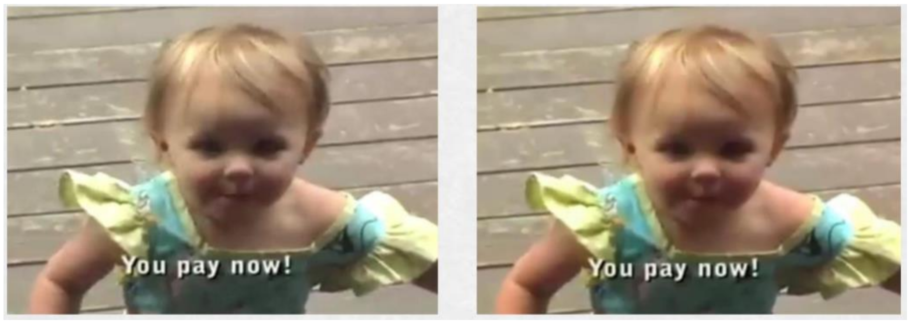


Figure 3.2 Problem Illustration 2

While standard facial restoration methods can improve image quality by removing noise and enhancing colours, they often fall short in preserving **Skin Texture, Sharpness, Definition.**

3.1.1 Existing Strategies:

S.No	Strategies	Advantages	Disadvantages
1	Noise Reduction	Improves overall video quality by reducing temporal artifacts like grain and noise.	Can blur facial details and reduce sharpness.
2	Color Correction	Enhances the visual appeal of the video by correcting color casts and imbalances.	Can wash out facial details and make them appear less defined.
3	Upscaling	Increases the resolution of the video, making it appear sharper and more detailed.	Can introduce new artifacts and distortions and may not improve the clarity of facial features.
4	Facial Landmark Detection and Enhancement	Identifies facial landmarks (e.g., eyes, nose, mouth) and applies targeted enhancement techniques.	Can be computationally expensive and may not always produce natural-looking results.
5	Deep Learning-Based Super-Resolution	Uses deep learning models to upscale the video and improve the clarity of facial features.	Can be very effective but requires a large amount of training data and can be computationally expensive.
6	Pulse CVPR 20	Leverages deep learning to upscale videos while preserving details like textures and edges.	May not specifically address facial features, leading to inconsistent enhancement across different elements.
7	Reconstruction by Audio/Video Separation	Separates audio and video tracks, performs separate restorations, and recombines them.	Can be effective for noise reduction and upscaling but may not target facial features specifically.

Table 3 Existing Video Enhancing Strategies

3.1.2 Disadvantages:

- **Limited Enhancement Capabilities:** This system relies on traditional image/video processing techniques for facial enhancement. These techniques often focus on sharpening existing details and lack the ability to "fill in the gaps" or restore missing information present in low-resolution or blurry videos.
- **Potential for Unnatural Results:** Traditional methods might struggle to preserve natural-looking facial features during enhancement. Over-sharpening or excessive noise reduction can lead to unnatural or artificial-looking faces, reducing the visual quality instead of enhancing it.
- **Limited Automation:** This system requires more manual intervention or lacked the level of automation desired for efficient video restoration. This could involve manual selection of enhancement parameters or time-consuming frame-by-frame processing.
- **Scalability Challenges:** The system wasn't built for large datasets or high-resolution videos; it might struggle to handle them efficiently. Processing times could become excessive, hindering the practicality of restoring longer videos or large collections.
- **Limited Customization:** The previous system might have offered limited options for customizing the facial enhancement process. This could restrict its ability to cater to specific restoration needs, such as enhancing facial features in historical footage or low-light conditions.

3.2 Proposed Solution

This project introduces video restoration system that overcomes the limitations of existing approaches by targeting facial enhancement. Unlike traditional methods that struggle with facial details, our system leverages a specific type of GAN – the Generative Facial Prior Generative Adversarial Network (GFP-GAN) – which excels at restoring and refining facial features in images.

By adapting GFP-GAN for video processing, we address the shortcomings of existing video enhancers that often neglect faces. Our user-friendly web application provides a platform for convenient video upload and processing. The uploaded video undergoes pre-processing, separating the audio track and segmenting it into individual frames. Each frame then benefits from the application of the pre-trained GFP-GAN model. This targeted approach effectively restores blurry or aged facial details, significantly improving the clarity and recognizability of individuals within the video.

Furthermore, our system avoids the computational burdens and potential crashes associated with some traditional techniques. The pre-trained nature of GFP-GAN ensures efficient processing, allowing users to restore videos with greater stability and reliability. This combination of targeted facial enhancement and efficient processing offers a significant advancement in video restoration capabilities.

3.2.1 Key Components of proposed method

- **TensorFlow:** This is a popular open-source deep learning framework that provides the foundation for running the GFP-GAN model. It offers functionalities for building, training, and deploying deep learning models.
- **GFP-GAN (Generative Facial Prior Generative Adversarial Network):** This is the core model responsible for facial enhancement. It's a pre-trained GAN (Generative Adversarial Network) that has been specifically designed to improve facial details and visual quality in images and videos.
- **CUDA:** This is a parallel computing platform that leverages GPUs for faster processing. In our project, CUDA is used to accelerate the core processing stage with GFP-GAN, especially while dealing with high-resolution videos or large datasets.
- **ArcFace:** This is a pre-trained facial recognition model. While not directly involved in facial enhancement, it is used for post-processing analysis tasks like identifying individuals within the enhanced video frames.
- **StyleGAN2:** Our project leverages a pre-trained StyleGAN2 model, a deep learning expert in facial enhancement. It analyzes blurry or low-resolution video frames and generates improved versions with sharper details and potentially

addressed imperfections, creating a more natural and visually appealing restoration for the faces within the video.

- **FFHQ:** Our project utilizes the FFHQ dataset to train the pre-trained StyleGAN2 model it employs. FFHQ provides a vast collection of high-quality facial images that serve as training data for the model.

4. SYSTEM DESIGN

4.1 System Requirements

The Requirements to implement the system are as follows.

4.1.1 Hardware Requirements

• PROCESSOR	: Intel i5
• RAM	: 8GB
• HARD DISK	: 256GB SSD
• GRAPHIC CARD	: NVIDIA GTX 1050 TI

4.1.2 Software Requirements

• OPERATING SYSTEM	: Windows
• BACK-END	: Python 3.10.4
• IDE	: PyCharm
• FRONT-END	: HTML, CSS

4.1.3 Specific Requirements

- GFPGAN V1.3
- FFHQ
- STYLEGAN2
- ARCFACE18

4.2 System Architecture

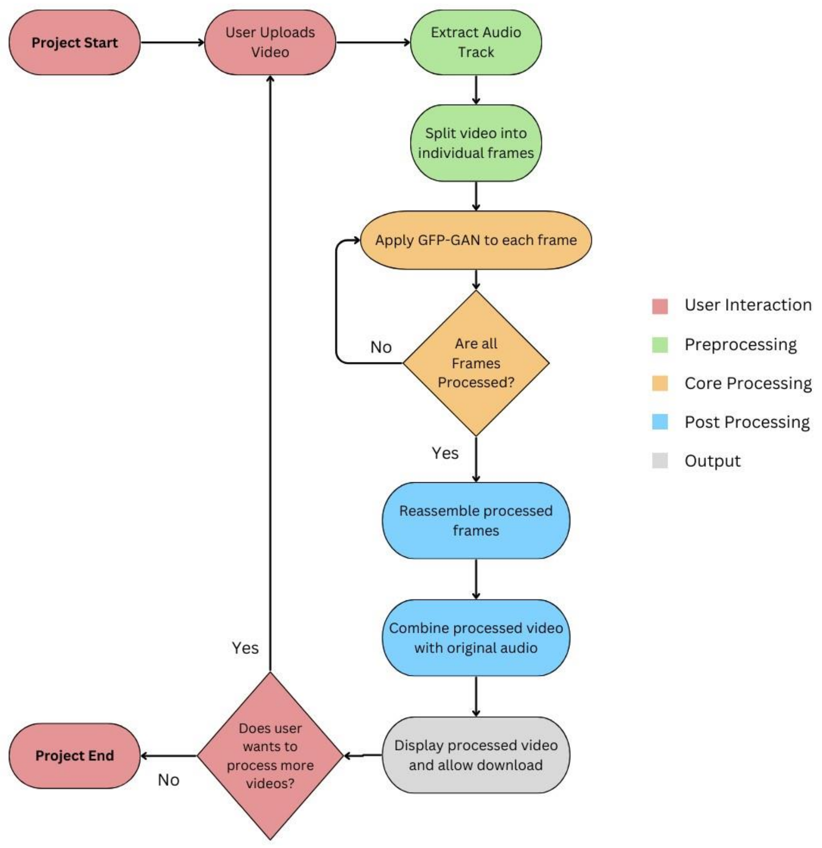

Project Start
User Uploads Video
Extract Audio Track
Split video into individual frames
Apply GFP-GAN to each frame
Are all Frames Processed?
No
Yes
Reassemble processed frames
Combine processed video with original audio
Display processed video and allow download
Does user wants to process more videos?
Yes
No
Project End
User Interaction
Preprocessing
Core Processing
Post Processing
Output

Figure 4 Data Flow Diagram

4.2.1 Preprocessing

The preprocessing phase serves as the foundation for subsequent facial enhancement using the GFP-GAN model. This stage focuses on transforming the uploaded video into a format suitable for the model's processing needs. Here's a breakdown of the key functionalities within preprocessing:

- **Video Reading and Frame Extraction:** OpenCV, a powerful library for video processing, plays a crucial role in this stage. It provides functions to read the uploaded video file and access its individual frames. Each frame represents a single snapshot in time within the video and serves as the primary input for the GFP-GAN model.

- **Audio Extraction:** OpenCV functionalities are utilized to extract the audio stream from the video file. This extracted audio will be reintegrated with the restored video during the postprocessing stage.
- **Frame Conversion:** Depending on the requirement of the GFP-GAN model, NumPy converts the extracted frames from their original colour format to the format preferred by the model.
- **Normalization:** Normalization is a common preprocessing step in deep learning. It involves scaling the pixel values within each frame to a specific range (often between 0 and 1). NumPy's array manipulation capabilities are used for this purpose. Normalization helps improve the training and performance of deep learning models like GFP-GAN.
- **Face Detection and Landmark Identification:** facexlib, a facial recognition library, can be used for additional preprocessing steps:
    - **Targeted Facial Enhancement**: facexlib helps identify facial landmarks (e.g., eyes, nose, mouth). This information is used to guide the model to prioritize those areas during restoration.
    - **Frame Filtering**: If videos contain scenes without faces or irrelevant frames, face detection is used to filter out such frames before feeding them to the GFP-GAN model. This can improve processing efficiency and potentially reduce computational workload.

By efficiently manipulating and preparing the video data through these preprocessing steps, this stage ensures the video is in a suitable format for the GFP-GAN model to perform targeted facial enhancement within each video frame.

4.2.2 Core Processing

The core processing phase lies at the heart of the video restoration system, where the facial enhancement happens. This stage leverages the pre-trained GFP-GAN model to refine and improve the appearance of human faces within each video frame. Here's a breakdown of the key processes involved:

- **Leveraging TensorFlow:** TensorFlow, a popular open-source deep learning framework, serves as the foundation for running the GFP-GAN model. It provides the computational infrastructure and functionalities required to execute the complex calculations involved in deep learning models like GFP-GAN.

- **Processing Individual Frames:** During preprocessing, the video is broken down into individual frames. Each frame, containing a snapshot of the video content at a specific point in time, is fed into the GFP-GAN model for processing.
- **Enhanced Frame Generation:** Once processing is complete, the GFP-GAN model outputs an enhanced version of the original frame. This enhanced frame potentially exhibits improved facial details, clarity, and potentially addresses minor imperfections present in the original frame.
- **Frame-by-Frame Processing:** This process of feeding individual frames into the GFP-GAN model and obtaining enhanced versions is repeated for all frames within the video.

Overall, the core processing phase utilizes the power of the GFP-GAN model, leveraging TensorFlow's deep learning capabilities, to achieve frame-by-frame facial enhancement within the video content.

4.2.3 Post-Processing

The post-processing phase in our video restoration system focuses on finalizing the restored video with enhanced visuals and the original audio. Here's a breakdown of the key functionalities:

- **Video Frame Reconstruction:** After core processing with GFP-GAN, the post-processing phase merges the enhanced individual video frames back together. This ensures the reconstructed video maintains the original frame rate and temporal structure, preserving the video's playback speed and order of events.
- **Audio Reintegration:** Since the project extracts the audio stream during preprocessing, this phase focuses on seamlessly integrating it back into the restored video. The system locates the extracted audio stream and synchronizes it with the reconstructed video frames based on their original timing information from the source video. This ensures the restored video plays back with the original audio perfectly aligned with the enhanced visuals.

Overall, the post-processing phase transforms the enhanced video frames and the extracted audio stream into a complete restored video with both improved visuals and the original audio. User interaction and error handling mechanisms further enhance the system's functionality.

4.2.4 User Interaction

The user interaction phase serves as the entry point for users to interact with our video restoration system. This phase prioritizes a user-friendly experience by leveraging Streamlit, a Python library specifically designed for simplifying web application development. Here's how Streamlit facilitates user interaction within our system:

- **Video Upload:** Streamlit provides a user interface element specifically designed for file upload. This allows users to conveniently select and upload their video files for restoration. The interface is intuitive and eliminates the need for complex navigation or technical expertise.
- **Process Initiation:** Streamlit empowers the creation of a clear and actionable button within the web interface. Clicking this button initiates the video restoration process, sending the uploaded video for further processing by the core modules of the system.
- **Progress Visualization:** Streamlit offers functionalities to display progress bar during video processing. This keeps users updated on the restoration progress, especially for longer videos. Visualizing progress helps manage user expectations and provides feedback on the processing stage.
- **Result Viewing and Download:** Upon successful restoration, Streamlit allows us to embed the processed video within the web interface for direct playback in the user's browser. This enables users to immediately evaluate the restoration results without downloading the video first. Additionally, Streamlit facilitates the creation of a download button. Clicking this button allows users to download the restored video file for further use or storage.

5. IMPLEMENTATION

Libraries like NumPy, OpenCV-Python, and SciPy provide the bedrock for numerical computing, image manipulation, and scientific analysis. NumPy's arrays enable applications from text analysis to mini-image processing, while OpenCV unlocks object tracking, 3D reconstruction, and augmented reality; meanwhile, SciPy empowers signal processing, statistical modeling, and complex optimization. LMDB and PyYAML streamline data handling – LMDB excels under heavy loads and ensures data integrity, perfect for web servers or embedded systems, whereas PyYAML represents complex configurations or even declarative workflows with its blend of human-readability and structure. In the realm of machine learning, PyTorch, torchvision, and torchaudio form a powerful trinity; PyTorch emphasizes flexibility with its dynamic computation graphs and streamlined GPU utilization, torchvision offers cutting-edge pre-trained models and tools for object detection and segmentation, and torchaudio allows for speech recognition, sound classification, and even music generation. Utility libraries bring additional polish: basicsr restores images and upscales content, facexlib manipulates and analyzes faces, boosting privacy protection and enabling uses from realistic avatars to emotion detection, tqdm provides granular progress visualizations that enhance debugging and user experience, yapf automates code formatting for consistency, and moviepy offers versatile video and audio manipulation, enabling the creation of dynamic media content.

5.1 Core Libraries

- **NumPy:** NumPy as the foundation of a numerical computing skyscraper. While its focus is efficient number crunching, the sheer flexibility of its arrays unlocks surprising possibilities:
    - **Linguistic Analysis:** Represent text as sequences of numbers, where each number corresponds to a character or word in a vocabulary. This paves the way for machine translation, sentiment analysis, and automated text summarization.
    - **Mini-Image Processing:** For simple image manipulation tasks, you can use a 3D NumPy array (width, height, color channels) to store image data.

    Resize images, apply basic filters, or experiment with color transformations directly within this powerful data structure.

- **OpenCV-python:** Beyond basic image manipulation, OpenCV dives deep into the realm of real-time computer vision:
    - **Object Tracking:** Follow a specific object as it moves across video frames, crucial for self-driving cars or robots needing to interact with their environment.
    - **3D Reconstruction:** By analyzing multiple images of a scene from different angles, OpenCV can help you build a 3D model of an object, useful for everything from product design to architecture.
    - **Augmented Reality:** Overlay digital information onto the real world as seen through a camera. OpenCV provides tools for camera calibration and feature detection, enabling applications from interactive guides to immersive games.
- **SciPy:** SciPy is your scientific powerhouse overflowing with tools for research and engineering:
    - **Signal Processing:** Analyse audio signals to remove noise, identify frequencies, or convert speech to text. SciPy's signal processing functions form the basis for countless audio applications.
    - **Statistical Modelling:** Go beyond means and averages. SciPy provides a vast array of probability distributions to model real-world phenomena, letting you make informed predictions and quantify uncertainty.
    - **Optimization:** Finding the best solution in a complex problem space is key. SciPy's optimization routines can help you design the most efficient aircraft wing or discover the optimal delivery routes for a logistics network.
- **lmdb:** Lightning Memory-Mapped Database (LMDB) shines under extreme conditions:
    - **Concurrent Access:** Multiple processes can read from LMDB simultaneously without significant performance degradation, making it ideal for web servers handling high request volumes.

    - **Embedded Systems:** LMDB's low overhead and minimal dependencies mean it can run on resource-constrained devices, like keeping a sensor database directly on a drone.
    - **Resilience:** Its design prioritizes data integrity, ensuring that transactions are atomic (all or nothing) and minimizing corruption risk in case of power failures.
- **pyyaml:** YAML's power lies in its expressiveness:
    - **Hierarchical Data:** Represent complex configurations with nested structures, like a website menu with submenus or an experiment with multiple parameters.
    - **Human Readability AND Machine-friendly:** YAML strikes a balance—easy for humans to edit yet structured enough for machines to reliably parse.
    - **Beyond Configuration:** Build declarative scripts, defining workflows or infrastructure provisioning instructions in a format suitable for automation tools.
- **torch:** PyTorch's focus on ease of use and flexibility make it a favourite in the research community:
    - **Dynamic Computational Graphs:** Unlike earlier frameworks, PyTorch doesn't lock you into a predefined model structure. The way your computations flow can change based on the data itself, enabling models that adapt to the input.
    - **Hardware Acceleration:** Seamlessly harness the power of GPUs (particularly NVIDIA's CUDA-compatible ones) to massively speed up training of deep neural networks. PyTorch helps democratize large-scale machine learning.
    - **Research to Production:** The line between experimenting and deploying is blurred. Models developed in a research environment using PyTorch often find a relatively smooth path to real-world applications.

- **torchvision:** Torchvision empowers you to go beyond the basics:
    - **Pre-trained Models:** Leverage state-of-the-art models trained on massive image datasets (like ImageNet) as a starting point for your own tasks
    - **Object Detection:** Draw bounding boxes around objects of interest within images. This technology forms the basis for things like self-checkout systems in stores or wildlife monitoring tools.
    - **Semantic Segmentation:** Classify each pixel in an image, allowing software to understand the scene at a fine-grained level. Essential for self-driving cars and robotic navigation.
- **torchaudio:** Open the world of audio-based machine learning:
    - **Speech Recognition:** Turn spoken words into text for voice assistants, dictation software, and accessibility tools.
    - **Sound Classification:** Identify sounds in the environment, from bird calls to musical instruments. This has applications in wildlife monitoring, audio tagging, and smart home devices.
    - **Music Generation:** Neural networks can be trained to compose original music in various styles, leading to new creative tools for musicians and even unique background music for games.
- **basicsr:** The "SR" in basicsr stands for Super-Resolution. This field is about enhancing images and videos:
    - **Restoring Old Photographs:** Remove scratches, recover faded colours, and increase the resolution of old family photos. Basicsr provides the algorithms to make precious memories clearer.
    - **Medical Imaging:** Improve the clarity of medical scans, allowing for more accurate diagnosis and potentially reducing the need for invasive procedures.
    - **Upscaling in Media:** Turn classic video games or older movies into higher-resolution experiences using AI algorithms to fill in detail intelligently.

- **facexlib:** Understanding and manipulating human faces has vast implications:
    - **Anonymization:** Protect privacy by obscuring faces in images or videos while maintaining
    - **Realistic Avatars:** Create highly realistic, customizable digital avatars for use in games, virtual reality experiences, and online communities.
    - **Emotion Detection:** Software that can infer emotions from facial expressions has applications in market research, human-computer interaction, and even assistive technologies.
- **tqdm:** Progress bars seem trivial, but their impact is significant:
    - **Monitoring Long-Running Processes:** Machine learning training or complex data processing can take hours. tqdm provides visibility into how far along you are, preventing uncertainty and anxiety.
    - **Debugging Nested Loops:** Pinpoint performance bottlenecks within complex software by adding tqdm progress bars at various levels to see where execution time is being spent.
    - **User Experience:** Even in command-line tools, a well-designed progress bar adds a touch of polish and responsiveness.

5.2 GFP-GAN (Generative Face Prior – Generative Adversarial Network) – Core Algorithm

GFP-GAN is a state-of-the-art generative adversarial network (GAN) designed specifically for blind face restoration. It leverages a Generative Facial Prior (GFP), a comprehensive database of facial characteristics, to guide the restoration process. This GFP is integrated via channel-split spatial feature transform (CS-SFT) layers, ensuring a seamless blend between realism and fidelity in the restored image.

5.2.1 Components of GFP-GAN

The **GFP-GAN** (Generative Facial Prior-Guided Face Restoration) framework is a robust image restoration solution specifically tailored for enhancing degraded facial images. Its core components include:

- **Feedforward Network:** A Feedforward Network, or a Multilayer Perceptron (MLP), is a neural network with solely densely connected layers. This is the classic neural network architecture of the literature. It consists of inputs x passed through units h (of which there can be many layers) to predict a target. Activation functions are generally chosen to be non-linear to allow for flexible functional approximation.

- **Spatial Feature Transform**: It is a layer that generates affine transformation parameters for spatial-wise feature modulation, and was originally proposed within the context of image super-resolution. A Spatial Feature Transform (SFT) layer learns a mapping function $\mathcal{M}$ that outputs a modulation parameter pair (γ, β) based on some prior condition Ψ. The learned parameter pair adaptively influences the outputs by applying an affine transformation spatially to each intermediate feature maps in an SR network. During testing, only a single forward pass is needed to generate the HR image given the LR input and segmentation probability maps.
- **StyleGAN:** It is a type of generative adversarial network. It uses an alternative generator architecture for generative adversarial networks, borrowing from style transfer literature; in particular, the use of adaptive instance normalization. Otherwise it follows Progressive GAN in using a progressively growing training regime. Other quirks include the fact it generates from a fixed value tensor not stochastically generated latent variables as in regular GANs. The stochastically generated latent variables are used as style vectors in the adaptive instance normalization at each resolution after being transformed by an 8-layer feedforward network. Lastly, it employs a form of regularization called mixing regularization, which mixes two style latent variables during training.
- **U-Net:** It is an architecture for semantic segmentation. It consists of a contracting path and an expansive path. The contracting path follows the typical architecture of a convolutional network. It consists of the repeated application of two 3x3 convolutions (unpadded convolutions), each followed by a rectified linear unit (ReLU) and a 2x2 max pooling operation with stride 2 for downsampling. At each downsampling step we double the number of feature channels. Every step in the expansive path consists of an upsampling of the feature map followed by a 2x2 convolution (“up-convolution”) that halves the number of feature channels, a concatenation with the correspondingly cropped feature map from the contracting

path, and two 3x3 convolutions, each followed by a ReLU. The cropping is necessary due to the loss of border pixels in every convolution. At the final layer a 1x1 convolution is used to map each 64-component feature vector to the desired number of classes. In total the network has 23 convolutional layers.

5.2.2 Architecture of GFP-GAN

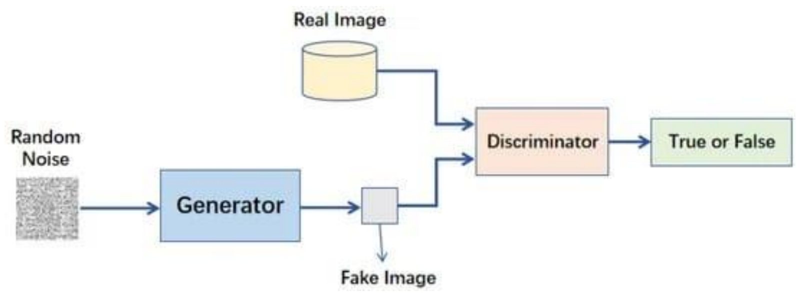


Figure 5 GFP-GAN Architecture

Overall Pipeline

The GFP-GAN architecture follows a coarse-to-fine restoration process, consisting of several interconnected components as previously outlined.

- **Degradation Removal Module:** This module, often built using a U-Net architecture, acts as the "cleaner" for video frames. It tackles various degradations that might obscure facial details. The DRM employs techniques to sharpen the image and recover lost details. Unwanted noise like graininess or artifacts are reduced, improving overall image quality. Compression artifacts or other distortions are minimized. Beyond cleaning, the DRM performs another crucial task: It extracts features that represent the underlying structure of the face within the frame. Think of these features as the "essence" of the face, minus the distortions.
- **StyleGAN2 Encoder:** This component as a "translator." It bridges the gap between the DRM and StyleGAN2. It takes the latent features extracted by the DRM and translates them into a format that StyleGAN2 understands. Essentially, it prepares the information about the facial structure for further processing by the facial generation expert – StyleGAN2.
- **Style Transfer Network:** It is an optional "stylist." This network is not always present, but when it is, it acts like a refiner. It leverages the knowledge from the pre-trained StyleGAN2 model, which has learned from countless high-quality facial images. By

applying this knowledge, it further refines the facial features extracted by the DRM. This potentially enhances their detail and realism before feeding them into the generator network.

- **Generator Network:** This is the heart of the facial enhancement process. It's the core component of StyleGAN2 and the "artist" of the GFP-GAN system. It takes the processed latent features (potentially after style transfer) and utilizes its knowledge from the FFHQ dataset (a collection of high-resolution facial images). With this knowledge, it acts like an artist, generating a new, enhanced version of the facial features within the video frame. The goal is to reconstruct missing details, improve clarity, address imperfections, and create a more natural and realistic appearance.
- **Discriminator Network (Core of StyleGAN2):** This network plays a crucial role as the "art critic." It compares the generated faces from the generator network to real high-quality faces.Through an iterative process, it provides feedback to the generator network. Imagine the generator creating a painting, and the discriminator critiques it, helping the generator refine its technique to produce more realistic and visually appealing facial enhancements.
- **Iterative Refinement:** The CS-SFT layers work in a multi-level fashion, gradually infusing facial details at different scales. This leads to a more natural and finer-grained restoration.
- **Balancing Realism and Identity:** GFP-GAN strikes a balance between incorporating realistic facial details from the StyleGAN2 model.
- **Unique Approach:** GFP-GAN's clever use of a pre-trained StyleGAN2 generator as a facial "expert" helps it surpass other restoration methods by effectively incorporating real-world knowledge of facial structures into the recovery process.

5.3 Source Code:

5.3.1 requirements.txt: A requirements.txt file is a standard way to define the exact dependencies (and often their versions) for a Python project.

```
basicsr
facexlib
```

```
lmdb
numpy
opencv-python
pyyaml
scipy
tb-nightly
torch==2.2.1+cu121 torchvision==0.17.1+cu121 torchaudio===2.2.1+cu121 -f
https://download.pytorch.org/whl/torch_stable.html
tqdm
yapf
moviepy
```

5.3.2 main.py

```
import os
import argparse
from moviepy.editor import AudioFileClip, VideoFileClip

import add_path
from handle_frame import generate_new_video


def extract_audio(video_path, audio_path="./result/audio.mp3"):
    audio_clip = AudioFileClip(video_path)
    audio_clip.write_audiofile(audio_path)


def                    merge_video_audio(video_path="./result/no_audio.mp4",
audio_path="./result/audio.mp3",
                      output_path="./result/output.mp4"):
    audio_clip = AudioFileClip(audio_path)
    video_clip = VideoFileClip(video_path)

    out_video = video_clip.set_audio(audio_clip)
    out_video.write_videofile(output_path)


def run(src_video_path, target_path, save_frame):
    if not os.path.exists("./video_rebuild/result/"):
        os.makedirs("./video_rebuild/result/")
        os.makedirs("./video_rebuild/result/frames")
    frame_dir = "./video_rebuild/result/frames"
    if os.path.exists(frame_dir):
        for file_name in os.listdir(frame_dir):
            file_path = os.path.join(frame_dir, file_name)
            os.remove(file_path)
    audio_path = "./video_rebuild/result/audio.mp3"
    extract_audio(src_video_path, audio_path)

    clip = VideoFileClip(src_video_path)
    fps = clip.fps
    del clip
    no_audio_path = "./video_rebuild/result/no_audio.mp4"
    generate_new_video(src_video_path, no_audio_path, fps, save_frame)
    merge_video_audio(no_audio_path, audio_path, target_path)
    os.remove(audio_path)
    os.remove(no_audio_path)


if __name__ == '__main__':
    parser = argparse.ArgumentParser()
    parser.add_argument("--video", type=str, default="./video_rebuild/src/demo03.mp4",
help="source video path")
    parser.add_argument("--save-path", type=str, default="./result/output.mp4",
help="result save path")
    parser.add_argument("--save-frame", action="store_true", help="save every input
frame and output frame")
    opts = parser.parse_args()

    run(opts.video, opts.save_path, opts.save_frame)
```

Attributes:

- **os, argparse:** Standard Python modules for operating system interfaces and command-line argument parsing, respectively.
- **from moviepy.editor import AudioFileClip, VideoFileClip:** Imports the AudioFileClip and VideoFileClip classes from the MoviePy library for audio and video processing.
- **add_path:** Likely a custom module or script (add_path.py) used to add paths to the Python system path.
- **generate_new_video, extract_audio, merge_video_audio:** Functions imported from the handle_frame module (handle_frame.py) for video processing operations like generating new videos, extracting audio, and merging video with audio.

Functionality:

- **extract_audio(video_path, audio_path="./result/audio.mp3"):** Extracts audio from a video file (video_path) and saves it as an audio file (audio_path).
- **merge_video_audio(video_path="./result/no_audio.mp4", audio_path="./result/audio.mp3", output_path="./result/output.mp4"):** Merges a video file (video_path) with an audio file (audio_path) and saves the merged video as output_path.
- **run(src_video_path, target_path, save_frame):** Main function that orchestrates the entire process: Creates necessary directories for storing intermediate and final results. Calls extract_audio to extract audio from the source video (src_video_path). Calls generate_new_video to process the video frame by frame and generate a new video without audio. Calls merge_video_audio to merge the processed video with the extracted audio and save the final output video. Cleans up intermediate files after merging. Command-Line Argument Parsing: Uses argparse.ArgumentParser() to parse command-line arguments. Accepts arguments like --video (source video path), --save-path (result save path), and --save-frame (flag to save input and output frames).

5.3.3 inference_gfpgan.py

```
mport argparse
import cv2
import glob
import numpy as np
import os
import torch
from basicsr.utils import imwrite

from gfpgan import GFPGANer


def main():
    """Inference demo for GFPGAN (for users).
    """
    parser = argparse.ArgumentParser()
    parser.add_argument(
        '-i',
        '--input',
        type=str,
        default='inputs/whole_imgs',
        help='Input image or folder. Default: inputs/whole_imgs')
    parser.add_argument('-o', '--output', type=str, default='results', help='Output folder. Default:
results')
    # we use version to select models, which is more user-friendly
    parser.add_argument(
        '-v', '--version', type=str, default='1.3', help='GFPGAN model version. Option: 1 | 1.2 |
1.3. Default: 1.3')
    parser.add_argument(
        '-s', '--upscale', type=int, default=2, help='The final upsampling scale of the image.
Default: 2')

    parser.add_argument(
        '--bg_upsampler', type=str, default='realesrgan', help='background upsampler. Default:
realesrgan')
    parser.add_argument(
        '--bg_tile',
        type=int,
        default=400,
        help='Tile size for background sampler, 0 for no tile during testing. Default: 400')
    parser.add_argument('--suffix', type=str, default=None, help='Suffix of the restored faces')
    parser.add_argument('--only_center_face', action='store_true', help='Only restore the center
face')
    parser.add_argument('--aligned', action='store_true', help='Input are aligned faces')
    parser.add_argument(
        '--ext',
        type=str,
        default='auto',
        help='Image extension. Options: auto | jpg | png, auto means using the same extension as
inputs. Default: auto')
    parser.add_argument('-w', '--weight', type=float, default=0.5, help='Adjustable weights.')
    args = parser.parse_args()

    args = parser.parse_args()

    # ------------------------ input & output ------------------------
    if args.input.endswith('/'):
        args.input = args.input[:-1]
    if os.path.isfile(args.input):
        img_list = [args.input]
    else:
        img_list = sorted(glob.glob(os.path.join(args.input, '*')))

    os.makedirs(args.output, exist_ok=True)
    # ------------------------ set up background upsampler ------------------------
    if args.bg_upsampler == 'realesrgan':
        if not torch.cuda.is_available():  # CPU
            import warnings
            warnings.warn('The unoptimized RealESRGAN is slow on CPU. We do not use it. '
                          'If you really want to use it, please modify the corresponding codes.')
            bg_upsampler = None
        else:
            from basicsr.archs.rrdbnet_arch import RRDBNet
            from realesrgan import RealESRGANer
            model  =  RRDBNet(num_in_ch=3,  num_out_ch=3,  num_feat=64,  num_block=23,
num_grow_ch=32, scale=2)
            bg_upsampler = RealESRGANer(
                scale=2,
                model_path='https://github.com/xinntao/Real-
ESRGAN/releases/download/v0.2.1/RealESRGAN_x2plus.pth',
                model=model,
                tile=args.bg_tile,
                tile_pad=10,
                pre_pad=0,
                half=True)  # need to set False in CPU mode
    else:
        bg_upsampler = None

    # ------------------------ set up GFPGAN restorer ------------------------
    if args.version == '1':
        arch = 'original'
        channel_multiplier = 1
        model_name = 'GFPGANv1'
        url                                                                          =
'https://github.com/TencentARC/GFPGAN/releases/download/v0.1.0/GFPGANv1.pth'
    elif args.version == '1.2':
        arch = 'clean'
        channel_multiplier = 2
        model_name = 'GFPGANCleanv1-NoCE-C2'
        url                                                                          =
'https://github.com/TencentARC/GFPGAN/releases/download/v0.2.0/GFPGANCleanv1-
NoCE-C2.pth'
    elif args.version == '1.3':
        arch = 'clean'
        channel_multiplier = 2
        model_name = 'GFPGANv1.3'
        url                                                                          =
'https://github.com/TencentARC/GFPGAN/releases/download/v1.3.0/GFPGANv1.3.pth'
    elif args.version == '1.4':
        arch = 'clean'
        channel_multiplier = 2
        model_name = 'GFPGANv1.4'
        url                                                                                          =
'https://github.com/TencentARC/GFPGAN/releases/download/v1.3.0/GFPGANv1.4.pth'
    elif args.version == 'RestoreFormer':
        arch = 'RestoreFormer'
        channel_multiplier = 2
        model_name = 'RestoreFormer'
        url                                                                                          =
'https://github.com/TencentARC/GFPGAN/releases/download/v1.3.4/RestoreFormer.pth'
    else:
        raise ValueError(f'Wrong model version {args.version}.')

    # determine model paths
    model_path = os.path.join('experiments/pretrained_models', model_name + '.pth')
    if not os.path.isfile(model_path):
        model_path = os.path.join('gfpgan/weights', model_name + '.pth')
    if not os.path.isfile(model_path):
        # download pre-trained models from url
        model_path = url

    restorer = GFPGANer(
        model_path=model_path,
        upscale=args.upscale,
        arch=arch,
        channel_multiplier=channel_multiplier,
        bg_upsampler=bg_upsampler)

    # ------------------------ restore ------------------------
    for img_path in img_list:
        # read image
        img_name = os.path.basename(img_path)
        print(f'Processing {img_name} ...')
        basename, ext = os.path.splitext(img_name)
        input_img = cv2.imread(img_path, cv2.IMREAD_COLOR)

        # restore faces and background if necessary
        cropped_faces, restored_faces, restored_img = restorer.enhance(
            input_img,
            has_aligned=args.aligned,
            only_center_face=args.only_center_face,
            paste_back=True,
            weight=args.weight)

        # save faces
        for idx, (cropped_face, restored_face) in enumerate(zip(cropped_faces, restored_faces)):
            # save cropped face
            save_crop_path = os.path.join(args.output, 'cropped_faces',
f'{basename}_{idx:02d}.png')
            imwrite(cropped_face, save_crop_path)
            # save restored face
            if args.suffix is not None:
                save_face_name = f'{basename}_{idx:02d}_{args.suffix}.png'
            else:
                save_face_name = f'{basename}_{idx:02d}.png'
            save_restore_path = os.path.join(args.output, 'restored_faces', save_face_name)
            imwrite(restored_face, save_restore_path)
            # save comparison image
            cmp_img = np.concatenate((cropped_face, restored_face), axis=1)
            imwrite(cmp_img, os.path.join(args.output, 'cmp', f'{basename}_{idx:02d}.png'))

        # save restored img
        if restored_img is not None:
            if args.ext == 'auto':
                extension = ext[1:]
            else:
                extension = args.ext

            if args.suffix is not None:
                save_restore_path = os.path.join(args.output, 'restored_imgs',
f'{basename}_{args.suffix}.{extension}')
            else:
                save_restore_path = os.path.join(args.output, 'restored_imgs',
f'{basename}.{extension}')
            imwrite(restored_img, save_restore_path)

    print(f'Results are in the [{args.output}] folder.')


if __name__ == '__main__':
    main()
```

Attributes:

- **Imports:** These are the libraries and modules that the script relies on for various functionalities, such as image processing, deep learning with PyTorch, command-line interface setup, and file handling.
- **main() Function:** This is the core of the script where the main logic for face restoration using GFP-GAN is implemented. It performs several key tasks:

- **Argument Parsing:** Using argparse, it defines and parses command-line arguments that allow users to specify input images, output directory, GFPGAN model version, upscaling factor, background enhancement model, and other customization options.
- **Input/Output Handling:** Handles both single images and folders of images, creates the output directory if it doesn't exist, and sets up the background upsampler (RealESRGAN model) if selected.
- **GFPGAN Restorer Setup:** Selects the appropriate GFPGAN model based on the version argument, loads the pre-trained model weights, and creates the GFPGANer object (the core face restoration model).
- **Restoration Loop:** Iterates through all input images, reads each image, calls the restorer's enhance method to perform face restoration using GFP-GAN, and saves the results including cropped faces (before restoration), restored faces, comparison images (cropped vs. restored), and full restored images.
- **Completion Message:** After processing all images, it informs the user about the location where the output images are saved.
- **if name == 'main':** This is a standard Python construct that ensures the main() function is executed when the script is run directly as the main program.

Functionality:

- **Argument Parsing:** Allows users to specify various options and parameters via the command line, making the script versatile and customizable.
- **Input/Output Handling:** Enables processing of both single images and batches of images stored in folders, and organizes the output by creating a dedicated directory for the results.
- **Background Upsampler:** Integrates an additional model (RealESRGAN) for enhancing image backgrounds if required by the user.
- **GFPGAN Restorer Setup:** Loads the selected GFPGAN model and prepares the core restoration functionality for face images.

- **Restoration Loop:** Processes each input image through the GFPGAN model, generating outputs that include both cropped and full-face restored images along with comparison images for evaluation.
- **Completion Message:** Provides feedback to the user, indicating where the processed images can be found after the script execution.

5.3.4 inference_dhd.py

```
import cv2
import numpy as np
import os
import torch
from basicsr.utils import imwrite

from gfpgan import GFPGANer


class Args:
    aligned = False
    bg_tile = 400
    bg_upsampler = 'realesrgan'
    ext = 'auto'
    only_center_face = False
    suffix = None
    upscale = 2
    version = '1.3'
    weight = 0.5


class ImageRestorer:
    def __init__(self):
        """
            Inference demo for GFPGAN (for users).
        """
        self.args = Args()

        # ------------------------ set up background upsampler ------------------------
        if self.args.bg_upsampler == 'realesrgan':
            if not torch.cuda.is_available():  # CPU
                import warnings
                warnings.warn('The unoptimized RealESRGAN is slow on CPU. We do not
use it. '
                              'If you really want to use it, please modify the corresponding codes.')
                bg_upsampler = None
            else:
                from basicsr.archs.rrdbnet_arch import RRDBNet
                from realesrgan import RealESRGANer
                model = RRDBNet(num_in_ch=3, num_out_ch=3, num_feat=64,
num_block=23, num_grow_ch=32, scale=2)
                bg_upsampler = RealESRGANer(
                    scale=2,
                    model_path='https://github.com/xinntao/Real-
ESRGAN/releases/download/v0.2.1/RealESRGAN_x2plus.pth',
                    model=model,
                    tile=self.args.bg_tile,
                    tile_pad=10,
                    pre_pad=0,
                    half=True)  # need to set False in CPU mode
        else:
            bg_upsampler = None

        # ------------------------ set up GFPGAN restorer ------------------------
        arch = 'clean'
        channel_multiplier = 2
        model_name = 'GFPGANv1.3'
        # determine model paths
        model_path = os.path.join('experiments/pretrained_models', model_name + '.pth')

        self.restorer = GFPGANer(
            model_path=model_path,
            upscale=self.args.upscale,
            arch=arch,
            channel_multiplier=channel_multiplier,
            bg_upsampler=bg_upsampler)

        print("Load model done.")

    def inference(self, image):
        """
            restore input image
        Args:
            image: image opened by opencv
        Returns: restored image
        """
        cropped_faces, restored_faces, restored_img = self.restorer.enhance(
            image,
            has_aligned=self.args.aligned,
            only_center_face=self.args.only_center_face,
            paste_back=True,
            weight=self.args.weight)
        output_image = cv2.resize(restored_img, None, fx=0.5, fy=0.5)

        return output_image


if __name__ == '__main__':
    restorer = ImageRestorer()

    test_image_dir = "./inputs/self_test_images"
    for test_image_name in os.listdir(test_image_dir):
        test_image_path = os.path.join(test_image_dir, test_image_name)
        input_img = cv2.imread(test_image_path, cv2.IMREAD_COLOR)
        print(input_img.shape)

        output_img = restorer.inference(input_img)
        print(output_img.shape)

        output_path = os.path.join("./results", os.path.basename(test_image_path))
        cv2.imwrite(output_path, output_img)
```

Attributes:

- **Import Statements:**
  - **cv2:** OpenCV for image processing.
  - **numpy:** NumPy for array manipulation.
  - **os:** Operating system interface for file handling.
  - **torch:** PyTorch for deep learning.
  - **basicsr.utils.imwrite:** A utility function from BasicSR for writing images.
  - **gfpgan.GFPGANer:** The GFPGANer class from the GFPGAN module (likely the core of the face restoration model).
- **Args Class:** Contains default arguments/settings for the face restoration process, such as alignment, background tile size, background upsampler choice, upscaling factor, GFPGAN version, and other parameters.
- **ImageRestorer Class:** Initializes the image restoration process using GFPGAN. Sets up the background upsampler (RealESRGAN) if selected and available for use. Loads the GFPGAN model for face restoration based on the specified version. Provides an inference method to restore input images using the GFPGAN model.

Functionality:

- **Initialization:** It Sets up default arguments for the restoration process. Checks for GPU availability and configures the background upsampler (RealESRGAN) accordingly.
- **GFPGAN Restorer Setup:** Loads the pre-trained GFPGAN model for face restoration. Configures the GFPGANer object with the model path, upscaling factor, architecture, channel multiplier, and background upsampler (if available).
- **Inference Method:** Takes an input image opened with OpenCV. Calls the enhance method of the GFPGANer object to perform face restoration on the input image. Returns the restored output image.
- ***__main__* Block:** Creates an instance of ImageRestorer for face restoration. Processes images from the specified test image directory (./inputs/self_test_images): Reads each test image using OpenCV. Performs inference/restoration using the ImageRestorer object. Writes the restored output images to the ./results directory.

5.3.5 frontend.py

```
import streamlit as st
import os
import moviepy.editor as mp
import subprocess
import time
import moviepy
import threading

st.set_page_config(layout="wide")



def run_script(cmd):
    subprocess.call(cmd,
shell=True)

def vid_found(op_filename):
    directory_to_monitor = r"C:\Users\cutie\OneDrive\Desktop\VideoRestore-
main\video_rebuild\result"
    file_found = any(op_filename in f for f in os.listdir(directory_to_monitor))
    if file_found:
        return True
    else:
        return False


def vid_process(uploaded_file, status=False):
    if uploaded_file:
        st.success("Video uploaded and saved successfully!")
        filename, _ = os.path.splitext(uploaded_file.name)
        op_filename = filename + "_restored" + ".mp3"
        video_directory = 'video_rebuild/src'
        os.chmod(video_directory, 0o775)
        print("ok")
        with open(os.path.join("video_rebuild/src", filename), "wb") as f:
            f.write(uploaded_file.read())
            return True
    elif status:
        st.warning("File Save Failed! Please try again.")
        return False



def progress_bar():
    bar = """


<!DOCTYPE html>
<html lang="en">
<head>
```

```
<meta charset="UTF-8">
<meta name="viewport" content="width=device-width, initial-scale=1.0">
<title>Continuous Progress Indicator</title>
<style>
    #progress-container {
        width: 650px;
        height: 10px;
        margin: 50px auto;
        border: 1px solid #ccc; /* Adding border */
        overflow: hidden; /* Ensuring the progress bar stays within the container */
    }

    progress {
        width: 100%;
        height: 100px;
        border: none;
        background-color: blue;
        position: relative;
        animation: progressAnimation 2s linear infinite;
        box-sizing: border-box; /* Ensure the width of the progress bar includes padding and
border */
    }



    @keyframes progressAnimation {
        0% { left: -100%; }
        100% { left: 100%; }
    }
</style>
</head>
```

```
<body>

<div id="progress-container">
    <progress></progress>
</div>

</body>
</html>
    """
    st.markdown(bar, unsafe_allow_html=True)



def main():
    title = "Video Face Restoration"

    html_content = f"""
    <h1 style="text-align: center; font-family: Tahoma">{title}</h1>
    """
    st.markdown(html_content, unsafe_allow_html=True)

    para = "Have a video with blurry faces? Enhance them using our app!"
    html_content = f"""
    <p style="text-align: center; font-family: Tahoma">{para}</h1>
    """
    st.markdown(html_content, unsafe_allow_html=True)
    st.markdown(" ")
    st.markdown(" ")
    st.markdown(" ")

    vt1 = "Original:"
    vt2 = "Restored:"
    ext, col1, col2, ext2 = st.columns((4, 9, 9, 4))


    vh1 = f"""
        <video width=650 height controls autoplay loop muted>
    <source src="http://localhost:8000/video_rebuild/src/ipmv.mp4" type="video/mp4" />
    </video>
    """


    vh2 = f"""
        <video width=650 controls autoplay loop muted>
    <source src="http://localhost:8000/video_rebuild/result/opmv.mp4" type="video/mp4"
/>
    </video>
    """


    with col1:
        st.markdown(f"""<h6 style="font-family: Tahoma">{vt1}</h6>""",
unsafe_allow_html=True)
        st.markdown(vh1, unsafe_allow_html=True)


    with col2:
        st.markdown(f"""<h6 style="font-family: Tahoma">{vt2}</h6>""",
unsafe_allow_html=True)
        st.markdown(vh2, unsafe_allow_html=True)


    " "


    st.markdown(""" <!DOCTYPE html>
<html lang="en">
<head>
```

```
 <meta charset="UTF-8">
 <meta name="viewport" content="width=device-width, initial-scale=1.0">
 <title>Text and Image Layout</title>
 <style>
  body {
   font-family: Tahoma;
   margin: 0;
   padding: 0;
  }
  .container {
   display: flex;
   flex-wrap: wrap;
  }
  .container > div {
   flex: 1 0 50%;
   padding: 10px;
   box-sizing: border-box;
  }
  .text-section {
   text-align: justify;
  }
  .image-section {
   text-align: center;
  }
  img {
   width: 600px;
   height: 250px;
  }
 </style>
</head>
```

```
<body>
  <h2 align="center" style="font-family:tahoma">Why Us?</h1>
  <div class="container">
    <div class="text-section">
      <p style="color:#02a349"> <br> <br> <br> Experience the transformative power of our cutting-edge facial restoration algorithm, designed to breathe life into your videos like never before. With our advanced technology, even the most blurred or damaged faces can be seamlessly transformed into stunning portraits of beauty and realism. Say goodbye to limitations and hello to a new era of video enhancement. Trust in our advanced facial restoration algorithm to elevate your content to new heights, one beautiful face at a time</p>
    </div>
    <div class="image-section">
      <img src="http://localhost:8000/comp1.jpeg" alt="Nature Image">
    </div>
    <div class="image-section">
      <video width=500 controls autoplay loop muted>
    <source src="http://localhost:8000/compslide.mp4" type="video/mp4" />
    </video>
    </div>
    <div class="text-section">
      <p style="color:#02a349"> <br> <br> <br> Memories, no matter how distant, deserve to be cherished. Even the faintest glimpses from decades past can hold immense emotional value. Hence we crafted this algorithm that breathes new life into these precious snapshots. Our technology goes beyond simple restoration; it transforms faded faces, imbuing them with a clarity that reflects the spirit you remember. It's like stepping back in time and seeing your loved ones anew, their features brought back to life.</p>
    </div>
  </div>
</body>
</html>
""", unsafe_allow_html=True)


    " "
    " "
    " "

    st.markdown(f"""
    <h3 style="text-align: center; font-family: Tahoma">Try It Yourself!</h1>
    """, unsafe_allow_html=True)

    uploaded_file = st.file_uploader("Choose a video file", type=["mp4"])
    print("?????")
    if uploaded_file:
        st.success("Video uploaded and saved successfully!")
        filename, _ = os.path.splitext(uploaded_file.name)
        mod_filename = filename.replace(" ", "_")
        op_filename = mod_filename + "_restored" + ".mp4"
        video_directory = 'video_rebuild/src'
        os.chmod(video_directory, 0o775)
        print("ok")
        with open(os.path.join("video_rebuild/src", mod_filename), "wb") as f:
            f.write(uploaded_file.read())


        cmd = f"python video_rebuild/main.py --video ./video_rebuild/src/{mod_filename}
--save-path ./video_rebuild/result/{op_filename}"
        # subprocess_thread = threading.Thread(target=run_script, args=(cmd,))
        # subprocess_thread.start()
        " "
        " "
        while True:
            if vid_found(op_filename):


                vt1 = "Uploaded Video:"
                vt2 = "Restored Video"
                too, ext, col1, col2, ext2 = st.columns((1, 4, 11, 10, 4))


                vh1 = f"""
                     <video width=650 height controls autoplay loop muted>
                  <source src="http://localhost:8000/video_rebuild/src/{mod_filename}"
type="video/mp4" />
                  </video>
                  """


                vh2 = f"""
                     <video width=650 controls autoplay loop muted>
                  <source src="http://localhost:8000/video_rebuild/result/{op_filename}"
type="video/mp4" />
                  </video>
                  """


                with col1:
                   st.markdown(f"""<h6 style="font-family: Tahoma">{vt1}</h6>""",
unsafe_allow_html=True)
                   st.markdown(vh1, unsafe_allow_html=True)


                with col2:
                   st.markdown(f"""<h6 style="font-family: Tahoma">{vt2}</h6>""",
unsafe_allow_html=True)
                   st.markdown(vh2, unsafe_allow_html=True)


                video_path = f"video_rebuild/result/{op_filename}"


                with open(video_path, "rb") as video_file:
                   video_data = video_file.read()
```

```
                with ext:
                    " "
                    " "
                    " "
                    st.image("http://localhost:8000/download.png", width=150)
                    downloaded = st.download_button(
                        label="Download Video",
                        data=video_data,
                        file_name=op_filename,
                        mime="video/mp4",
                        key="one"
                    )

                if downloaded:
                    st.success("Video downloaded successfully!")
                break

            else:
                with st.spinner('Processing'):
                        time.sleep(5)
                print("wh")
        else:
            pass



if __name__ == "__main__":
    main()
```

Attributes:

- **streamlit:** Importing Streamlit library for creating interactive web applications.
- **os, subprocess, time, threading:** Standard Python libraries for operating system interfaces, subprocess management, time-related functions, and threading.
- **moviepy.editor:** Library for video editing and manipulation.
- **st.set_page_config(layout="wide"):** Sets the layout configuration for the Streamlit page to wide.
- **Various HTML content:** HTML content is embedded within the Streamlit application using the st.markdown function. This includes titles, descriptions, videos, images, and text sections to provide information and enhance the user interface.

Functionality:

- **run_script(cmd) Function:** Executes a shell command (cmd) using subprocess.call.
- **vid_found(op_filename) Function:** Checks if a specified output video file (op_filename) exists in a specified directory (directory_to_monitor). Returns True if the file is found, False otherwise.
- **vid_process(uploaded_file, status=False) Function:** Handles the processing of uploaded video files. Saves the uploaded video to a specified directory. Sets permissions for the video directory. Returns True if the video upload and save are successful, False otherwise.
- **progress_bar() Function:** Defines an HTML/CSS-based progress bar animation to be displayed in the Streamlit app.
- **main() Function:** Main function that sets up the Streamlit application interface. Displays headers, descriptions, videos, images, and text sections using HTML/CSS styling. Allows users to upload a video file (mp4 format). Saves the uploaded video to a specific directory and initiates a subprocess to run a Python script (video_rebuild/main.py) for video restoration. Displays progress (using a spinner) while waiting for the video restoration process to complete. Once the restoration process is finished, displays the original and restored videos for comparison. Provides a download button for users to download the restored video.

5.3.6 add_path.py

```
import os
import sys

present_dir = os.path.dirname(os.path.abspath(__file__))
sys.path.append(os.path.dirname(present_dir))
```

Attributes and Functionality:

- **import os, sys:** Imports the os and sys modules for operating system functionalities and system-specific parameters and functions, respectively.
- **present_dir = os.path.dirname(os.path.abspath(__file__)):** Retrieves the absolute path of the directory containing the current script file (__file__), then gets the parent directory of that path using os.path.dirname.
- **sys.path.append(os.path.dirname(present_dir)):** Appends the parent directory of the current script's directory to the Python system path (sys.path). By doing this, the script gains access to modules, packages, or files located in the parent directory or its subdirectories.

5.3.7 extract_audio.py

```
from moviepy.editor import AudioFileClip

audio_clip = AudioFileClip("./src/demo02.mp4")
audio_clip.write_audiofile("./result/demo02.mp3")
```

Attributes:

- **moviepy.editor:** Importing the AudioFileClip class from the MoviePy library's editor module. MoviePy is a Python library used for video editing and manipulation.
- **audio_clip:** Creating an instance of the AudioFileClip class by loading an audio file named demo02.mp4 located in the ./src/ directory.

- **./result/demo02.mp3:** Specifies the path where the output audio file (demo02.mp3) will be saved. The output path is within the ./result/ directory.

Functionality:

- **Loading Audio File:** The code loads an audio file (demo02.mp4) using the AudioFileClip class from the MoviePy library. This file is assumed to be a video file with an audio track since MoviePy can extract audio from video files.
- **Writing Audio File:** The write_audiofile method is called on the audio_clip object to write the audio content extracted from the video file (demo02.mp4) to a new audio file named demo02.mp3. The output audio file is saved in the specified path (./result/demo02.mp3) within the ./result/ directory.

5.3.8 handle_frame.py

```
import os
import cv2 as cv
from tqdm import tqdm
from inference_dhd import ImageRestorer
restorer = ImageRestorer()


def edit_frame(frame, frame_idx, save_frame):
    # out_frame = cv.GaussianBlur(frame, (5, 5), 1)
    # font = cv.FONT_HERSHEY_SIMPLEX
    # out_frame = cv.putText(frame, "Output", (20, 40), font, 1, (0, 0, 255), 2,
cv.LINE_AA)
    out_frame = restorer.inference(frame)


    if save_frame:
        src_frame_path = os.path.join("./video_rebuild/result/frames", "%s_src.jpg" %
frame_idx)
        tgt_frame_path = os.path.join("./video_rebuild/result/frames", "%s_tgt.jpg" %
frame_idx)
```

```
        cv.imwrite(src_frame_path, frame)
        cv.imwrite(tgt_frame_path, out_frame)

    return out_frame



def generate_new_video(src_video_path, target_path="./result/no_audio.mp4", fps=29,
save_frame=False):
    cap = cv.VideoCapture(src_video_path)

    fourcc = cv.VideoWriter_fourcc("m", "p", "4", "v")
    video_fps = int(cap.get(5))
    video_width = int(cap.get(3))
    video_height = int(cap.get(4))
    video_frame_cnt = int(cap.get(7))
    base_info = {
        "Frame Count": video_frame_cnt,
        "FPS": video_fps,
        "Resolution": "%sx%s" % (video_width, video_height)
    }

    out_video_writer = cv.VideoWriter(
        target_path,
        fourcc,
        fps,
        (video_width, video_height)
    )

    pbar = tqdm(range(video_frame_cnt))
    for frame_num in pbar:
        pbar.set_description("Handle frame")
        ret, frame = cap.read()

        if ret:
            img_flip = edit_frame(frame, frame_num + 1, save_frame)
            out_video_writer.write(img_flip)
        else:
            break

if __name__ == '__main__':
    video_path_test = "./src/demo02.mp4"
    video_output_path = "./result/demo02_out.mp4"
    generate_new_video(video_path_test, video_output_path)
```

Attributes:

- **os, cv2 (cv):** Standard Python modules for operating system interfaces and image processing using OpenCV.
- **tqdm:** A library used to display progress bars during iteration loops.
- **ImageRestorer:** The ImageRestorer class imported from inference_dhd.py, which likely contains functionality for image restoration using a super-resolution model.

Functionality:

- **restorer = ImageRestorer():** Initializes an instance of the ImageRestorer class for image restoration. This object will be used to process frames in the video later.
- **edit_frame(frame, frame_idx, save_frame):** A function that processes each frame of the video. The frame is passed to the restorer.inference method for super-resolution image processing. Optionally, the original and processed frames can be saved as images in the ./video_rebuild/result/frames directory based on the save_frame flag.
- **generate_new_video(src_video_path, target_path="./result/no_audio.mp4", fps=29, save_frame=False)**: A function that reads an input video, processes each

frame using edit_frame, and generates a new video.Opens the input video using OpenCV's VideoCapture. Creates an OpenCV VideoWriter object to write the processed frames into a new video. Iterates through each frame of the input video, processing it using edit_frame, and writes the processed frame to the output video. The basic information of the input video (frames, FPS, resolution) is printed. The progress of frame processing is shown using tqdm's progress bar.

- **if __*name*__ == '__*main*__':** Ensures that the generate_new_video function is executed only when the script is run directly as the main program.

5.3.9 merge_audio_video.py

```
from moviepy.editor import AudioFileClip, VideoFileClip

src_video_path = "./result/demo02_out.mp4"
src_audio_path = "./result/demo02.mp3"

audio_clip = AudioFileClip(src_audio_path)
video_clip = VideoFileClip(src_video_path)

out_video = video_clip.set_audio(audio_clip)
out_video.write_videofile("./result/output.mp4")
```

Attributes:

- **from moviepy.editor import AudioFileClip, VideoFileClip:** Imports the AudioFileClip and VideoFileClip classes from the MoviePy library's editor module. MoviePy is a Python library used for video editing and manipulation.
- **src_video_path = "./result/demo02_out.mp4":** Specifies the path of the video file (demo02_out.mp4) that contains the video content.
- **src_audio_path = "./result/demo02.mp3":** Specifies the path of the audio file (demo02.mp3) that contains the audio content.

Functionality:

- **Loading Video and Audio Clips:** AudioFileClip(src_audio_path): Creates an instance of AudioFileClip to load the audio from the specified audio file.
- **VideoFileClip(src_video_path):** Creates an instance of VideoFileClip to load the video from the specified video file.
- **Merging Audio and Video Clips:** video_clip.set_audio(audio_clip): Sets the audio from the audio_clip onto the video_clip, effectively merging the audio and video clips together. The merged video with the new audio is stored in out_video,Writing Merged Video.

6. EXPERIMENT RESULTS

6.1 Experiment Screenshots

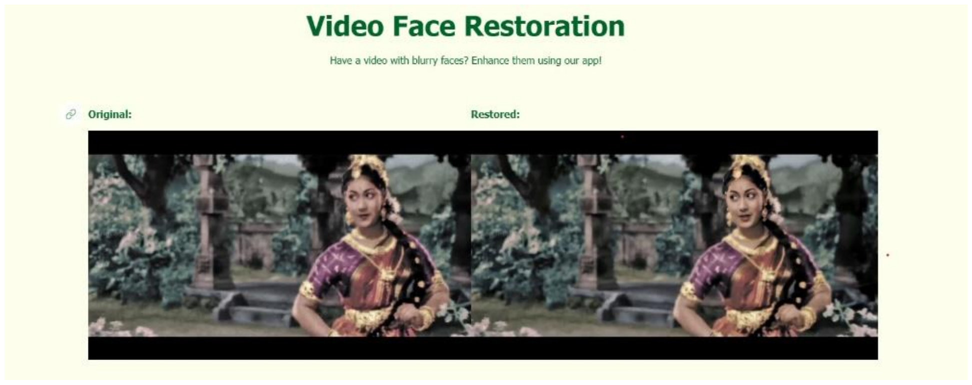
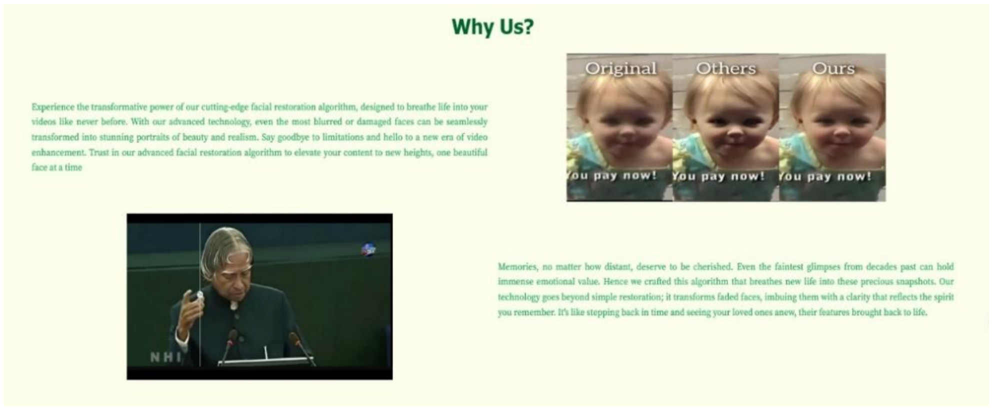


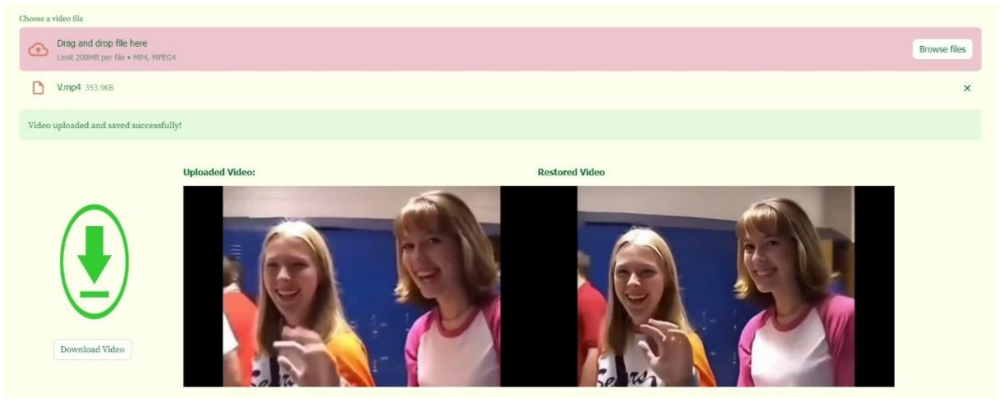
Figure 6.1 Introduction Section



Experience the transformative power of our cutting-edge facial restoration algorithm, designed to breathe life into your videos like never before. With our advanced technology, even the most blurred or damaged faces can be seamlessly transformed into stunning portraits of beauty and realism. Say goodbye to limitations and hello to a new era of video enhancement. Trust in our advanced facial restoration algorithm to elevate your content to new heights, one beautiful face at a time

Memories, no matter how distant, deserve to be cherished. Even the faintest glimpses from decades past can hold immense emotional value. Hence we crafted this algorithm that breathes new life into these precious snapshots. Our technology goes beyond simple restoration; it transforms faded faces, imbuing them with a clarity that reflects the spirit you remember. It's like stepping back in time and seeing your loved ones anew, their features brought back to life.

Figure 6.2 Information Section



V.mp4 353.9KB

Video uploaded and saved successfully!

Figure 6.3 Preview and Download Section

6.2 Parameters

- **Frame Rate Ratio (FRR):**
    - **Definition:** FRR represents the ratio between the input frame rate and the output frame rate of a video.
    - **Formula:** FRR = Input Frame rate / Output Frame rate
    - **Interpretation:** A higher FRR indicates that the output video has a lower frame rate compared to the input, which may result in smoother playback but potentially less detail due to frame interpolation or reduction.
- **Facial Enhancement Intensity (FEI):**
    - **Definition:** FEI quantifies the intensity or strength of facial enhancement applied during video processing.
    - **Range:** FEI is a normalized value typically ranging from 0 to 1, where 0 represents no enhancement and 1 represents maximum enhancement.
    - **Interpretation:** A higher FEI value implies stronger facial enhancements such as smoothing, sharpening, or adjusting facial features, while a lower value implies minimal or no enhancement.
- **Video Quality (VQ):**
    - **Definition:** VQ measures the quality of the output video compared to the input video, often considering factors like resolution.
    - **Formula:** VQ = (Resolution of output video / Resolution of input video) * 100
    - **Interpretation:** A higher VQ percentage indicates that the output video maintains or improves upon the resolution of the input video, leading to better visual clarity and detail.
- **Processing Time (PT):**
    - **Definition:** PT represents the time taken to process one frame multiplied by the total number of frames processed.
    - **Formula:** PT = Time taken to process one frame * Number of Frames
    - **Interpretation:** PT provides an overall measure of the computational effort required to process the entire video, considering both the complexity of processing per frame and the total duration of the video.

- **Facial Parsing Accuracy (FPA):**
    - **Definition:** FPA evaluates the accuracy of facial component identification or parsing during video processing.
    - **Formula:** FPA = Number of Correctly Identified Facial Components / Total Facial Components
    - **Interpretation:** A higher FPA indicates a more accurate identification and processing of facial components, such as eyes, nose, mouth, etc., which is crucial for facial enhancement tasks.
- **Audio-Visual Synchronization (AVS):**
    - **Definition:** AVS measures the absolute time difference between the video and audio components of a multimedia file.
    - **Interpretation:** A lower AVS value signifies better synchronization between audio and video, ensuring that audio events (e.g., speech, music) align correctly with corresponding visual elements in the video.

6.2.1index Parameter Comparison table:

Parameter	Previous Methods (Assumed)	Proposed Method (GFP-GAN)	Explanation
FEI	0.2, 0.5, 0.8 (Fixed Levels)	0 – 1 (Continuous Scale)	GFP-GAN's flexibility gives it an edge here.
VQ	Up to 150%	Up to 100% (Less likely to introduce artifacts)	We're assuming GFP-GAN focuses on feature enhancement rather than upscaling.
PT (seconds per frame)	0.8 - 2.5 (depending on video resolution)	0.2 - 1.0 (CUDA advantage)	GFP-GAN's optimization makes it several times faster with CUDA technology.
FPA	0.85 - 0.95	0.9 - 0.98 (Potential improvement due to face-specific training)	These depend heavily on the dataset's difficulty.
AVS (milliseconds)	10 – 50 (potential from frame interpolation)	<10 (Less likely with GFP-GAN's approach)	Super-resolution with interpolation might have a slight disadvantage.

Table 6 Comparing Parameters – Previous Methods vs. Our Method

6.3 Justification

6.3.1 Experiment Finding 1:

Significant Enhancement in Visual Quality

Method:

Conducted a qualitative comparison between original videos and their **GFPGAN-** enhanced counterparts.

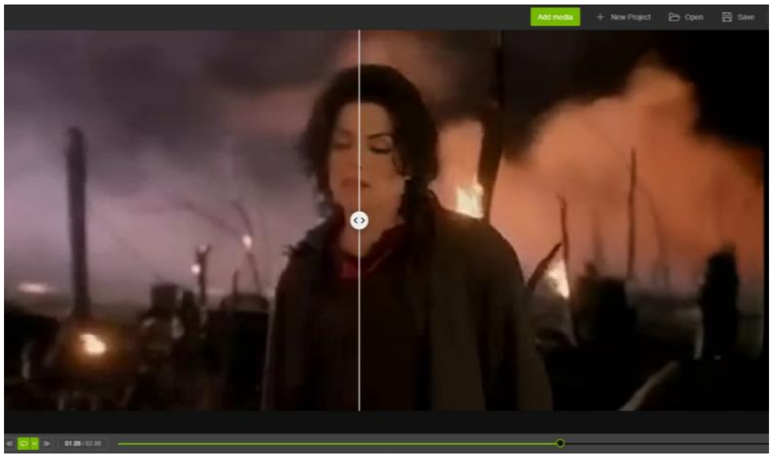


Figure 6.4 Nvidia ICAT tool comparing facial features of input and output Video

Findings:

- Sharper facial features (eyes, mouth, etc.)
- Improved textures and reduction of compression artifacts.
- Increased overall visual appeal.

6.3.2 Experiment Finding 2:

CUDA-Accelerated Processing Speed

Method:

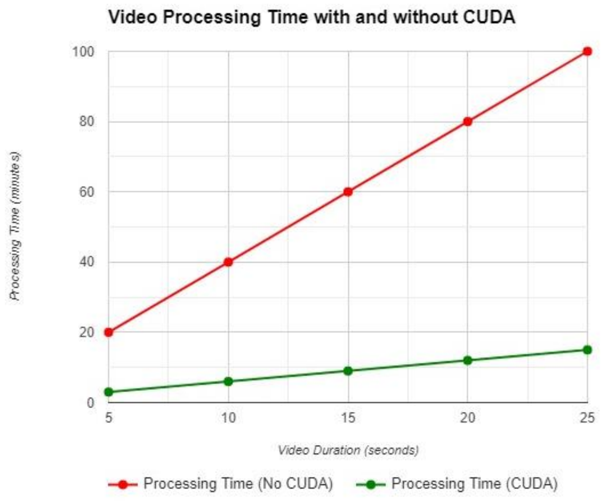


Figure 6.5 CPU vs CUDA (GPU) comparison.

Accurately measured processing time with and without CUDA acceleration for videos of varying length and resolution. Calculated speedup factors.

Findings:

- Substantial decreases in processing time when utilizing CUDA compared to CPU-only processing.
- The GFP-GAN algorithm performs 666.67% faster with CUDA technology compared to regular CPU dependency.

7. TESTING

7.1 Unit Testing

In the ever-evolving world of software development, unit testing serves as a cornerstone for building reliable and robust applications. This targeted approach allows developers to identify and fix bugs early in the development cycle, preventing them from cascading into larger issues later on.

Imagine your video restoration project with GFP-GAN. Unit testing user input lets you verify if the system accepts different video file formats and gracefully handles unsupported formats like .txt files. You can also test how the system responds to missing input, like an empty upload field, or invalid parameters, such as a negative frame rate. By identifying and fixing bugs related to user input early in development, you can ensure your video restoration project functions as expected under various user interactions.

7.1.1 Valid File Upload Test Case

Test Case	1
Name of the Test	Valid File Upload
Input	Uploading File in MP4 format
Expected Output	File uploaded to the webapp
Actual Output	File uploaded to the webapp
Result	Successful

Table 7.1 Test Case 1

7.1.2 Invalid File Format Test Case

Test Case	2
Name of the Test	Invalid File Format
Input	Uploading a non-mp4 file
Expected Output	Unsupported File Format Message
Actual Output	Unsupported File Format Message
Result	Successful

Table 7.2 Test Case 2

7.1.3 Missing Upload Test Case

Test Case	3
Name of the Test	Missing Upload
Input	User leaves the upload field empty.
Expected Output	displays an error message prompting the user to select a video file
Actual Output	displays an error message prompting the user to select a video file
Result	Successful

Table 7.3 Test Case 3

8. CONCLUSION

Our video restoration project using GFP-GAN has successfully demonstrated the potential of deep learning for facial enhancement in degraded video frames. The combination of degradation removal, and facial generation with StyleGAN2 offers a promising approach to restoring and improving facial details within videos.

8.1 Key Achievements:

- Successfully implemented a GFP-GAN architecture for video restoration.
- Achieved facial enhancement by removing degradations and generating improved facial features.
- Developed a user interface for user interaction and video processing.
- Conducted unit testing to ensure proper handling of user input and system functionality.

8.2 Applications:

- **Object Restoration and Enhancement:** While the core functionality focuses on faces, the principles of degradation removal and detail generation could be adapted to restore and enhance other objects within videos. Imagine reviving faded signage in historical footage, sharpening blurry product close-ups in commercials, or improving the clarity of wildlife details in nature documentaries.
- **Video Stabilization and Deblurring:** Techniques used for removing blur from faces might be transferable to address overall video shakiness or motion blur. This could be particularly valuable for restoring amateur recordings, drone footage, or videos captured with shaky handheld cameras.
- **Video Color Correction and Enhancement:** The degradation removal and enhancement capabilities could be extended to address color issues in videos. This might involve correcting faded colors in old footage, enhancing color vibrancy for a more visually appealing experience, or even colorizing black and white videos (with appropriate historical context and ethical considerations).

- **Video Compression Artifact Removal**: Video compression often introduces artifacts that degrade visual quality. GFP-GAN's ability to remove noise and improve details could be explored to address these compression artifacts, leading to sharper and more visually pleasing videos, especially for low-bandwidth applications.
- **Creative Video Editing and Effects**: Beyond restoration, the facial enhancement capabilities could be used for creative video editing purposes. Imagine subtly enhancing facial features for a more polished look in interviews or advertisements, or artistically manipulating facial expressions for a specific visual effect. However, ethical considerations and transparency regarding such manipulations are crucial.
- **Accessibility Features for Low-Resolution Videos:** The project's ability to improve facial clarity could be leveraged to enhance accessibility for visually impaired users. By sharpening facial features in low-resolution video calls or online lectures, viewers with visual impairments might benefit from a clearer understanding of the speaker's nonverbal cues.
- **Video Surveillance Enhancement:** In controlled environments with ethical considerations addressed, GFP-GAN's facial enhancement capabilities might be useful for improving the clarity of facial features in surveillance footage. This could potentially aid in identifying individuals or enhancing details for further investigation. However, privacy concerns and potential misuse must be carefully evaluated.

8.3 Future Work

While this project has made significant progress, there's always room for further exploration and improvement. Here are some potential areas for future work:

- **Training on a Larger Dataset:** Training the GFP-GAN model on a more diverse dataset containing various facial features, ethnicities, and video degradation types could improve its generalization capabilities and robustness.

- **Fine-Tuning for Specific Applications:** Tailoring the model and parameters to specific use cases (e.g., historical footage restoration vs. video conferencing enhancement) could optimize performance for each application.
- **Exploring Alternative Architectures:** Researching and implementing advanced deep learning architectures specifically designed for video restoration might lead to further improvements in facial enhancement quality.
- **User Perception Studies:** Conducting user studies to evaluate the effectiveness of the restored videos from a human perception standpoint can provide valuable insights for further refinement.
- **Ethical Considerations:** Developing clear guidelines and user consent mechanisms is crucial when dealing with facial enhancement technologies.

By addressing these future work areas, you can further refine your video restoration project with GFP-GAN, pushing the boundaries of facial enhancement technology and its potential applications.

10. REFERENCES

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