Pixel Steganography

PySteg
Encoding In Images With Further Encryption

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1 Analysis

1.1 Overview

This project aims to create a graphical tool designed for pixel steganography and image conversion, offering a quick way to show just how powerful hiding data in images can be. Pixel steganography is a technique used to hide data within the pixels of an image, making the data invisible to the naked eye, with the data then able to be extracted later. The application should include multiple pages: one for embedding data into images using pixel steganography, another for decoding hidden data from images, another for creating a configuration to determine how to encrypt, and a final one for converting between different image file formats (e.g., JPG to PNG). This functionality will enable users, particularly in a classroom setting, to visualise and understand what steganography is and how it potentially could look by embedding and extracting hidden information within images.

1.2 The Problem

In educational environments, offering students tools that help understand complex concepts visually can significantly help with the learning process. Data hiding (cryptography) with image processing is often challenging, and existing image steganography tools lack user-friendliness and educational focus needed for classroom use. Steganography tools typically support only a single file type, and non-integrated conversion tools can put students off by reducing ease of use.

There is a tradeoff between usability and tool comprehensiveness; some tools are user-friendly but lack features that could help develop a deeper understanding, such as the ability to choose specific pixel placement, encryption methods, and subtlety levels. Advanced tools often have vague interfaces, making it difficult for students to understand the processes involved.

Batch processing and performance are often quite miserable in current tools. In a classroom setting, the ability to process multiple images simultaneously is useful for demonstrating the scalability and efficiency of different steganography techniques. Poor performance, especially slow processing times, can negatively affect learning experience, particularly with high-res images.

Security of embedded data is often compromised due to poor encryption techniques, with many tools lacking robust logic to ensure hidden data remains secure against unauthorised access or tampering. Understanding data security is crucial for students, as it teaches that sometimes one layer of encryption is insufficient.

In summary, existing graphical pixel steganography tools fail to balance usability, functionality, security, and performance. This project aims to address these issues by developing an application that provides a user-friendly interface, supports multiple file types, includes advanced features for maintaining image integrity, enables batch processing, ensures data security, and delivers efficient performance.

1.3 Online Tools

1.3.1 stego.js.org

As you can see, this solution is very much on the user-friendly side of things. However, this obviously does have drawbacks. Although it allows the user to choose from 6 levels (it indexes from 0), you realistically wouldn't want to go above level 2.

Figure 1: Original Image

(a) Level 0 (b) Level 1

(c) Level 2 (d) Level 3

(e) Level 4 (f) Level 5

Figure 2: Examples of the stego images for the particular level of steg applied

There are quite a few issues with this tool. To begin, it massively downscaled the resolution of images (in my test it reduced by a scale factor of 7.264). It also very evidently became obvious to the eye that the image probably had something going on from level 2, making it pretty ineffective going higher than that despite promising greater data secrecy. There also weren't that many things to choose from or customise yourself as the user, only allowing choice from predefined levels and a password for encryption/decryption, making it slightly harder to understand what it was actually doing. Finally, it didn't attempt any steganalysis at all; with only 6 levels to choose from, it could've had a toggle to check all of them in case the user forgot what they had encrypted with.

Benefits / Drawbacks Summary:

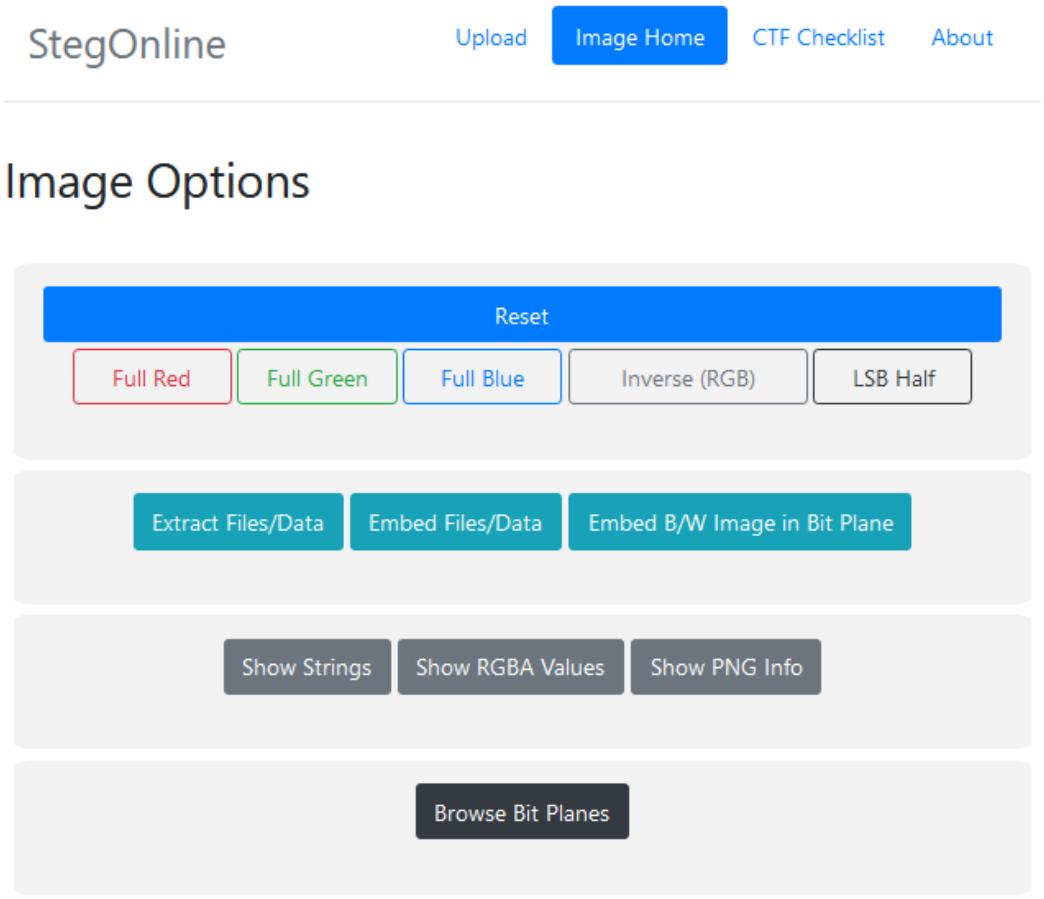
+ Interface is very easy to use

+ Offers a good compression rate for images so don't take up much space.

- Not much control on how data is secured - no insight into the encryption measures.

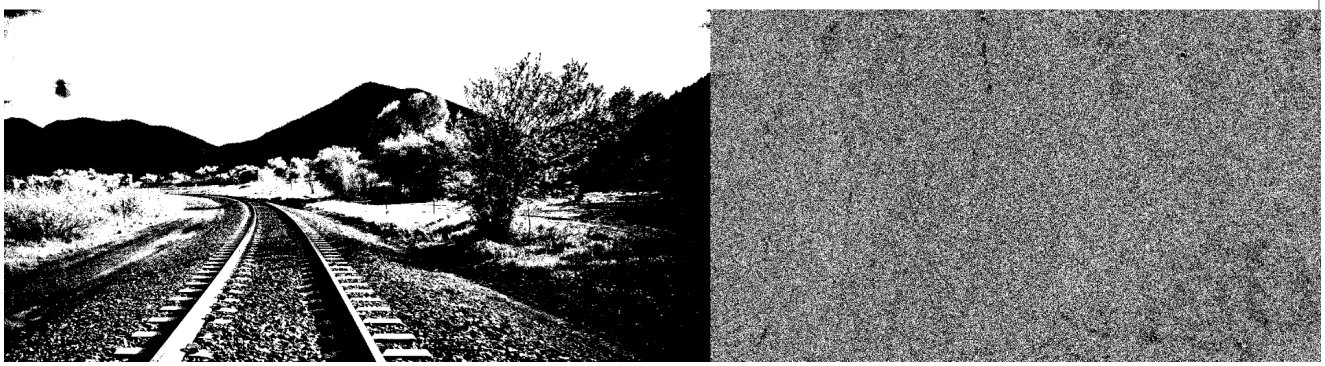
- No option to control compression rate and so image resolution might be downsized when you don't want it to be.

1.3.2 georgeom.net/StegOnline



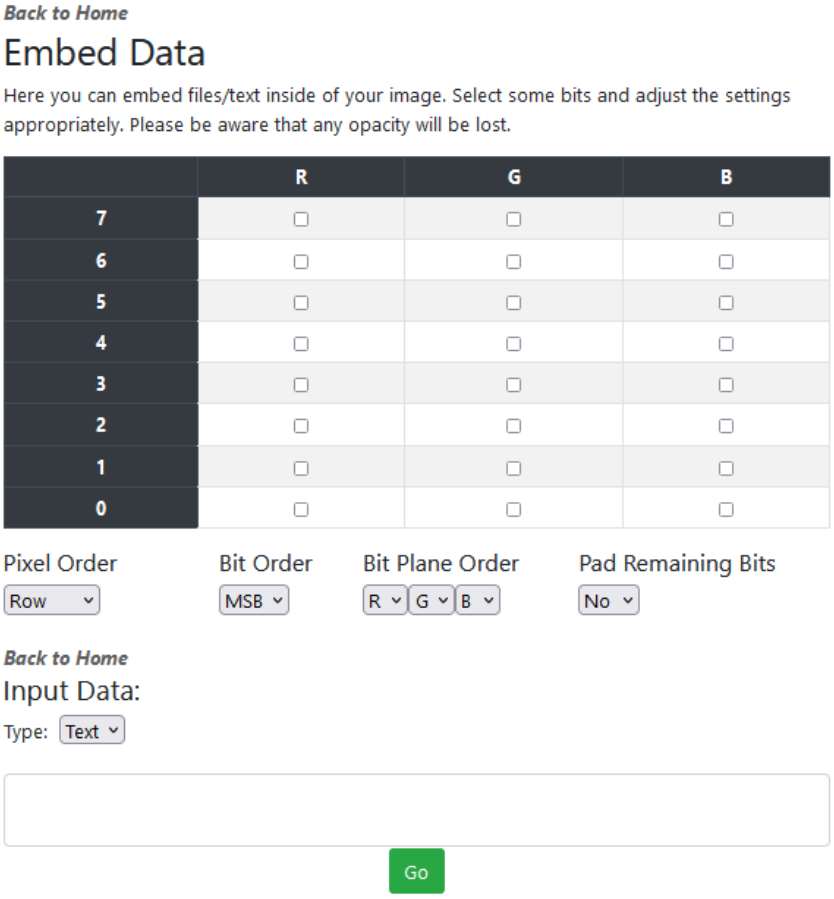
This tool offers a more advanced set of features compared to stego.js.org, but comes with its own challenges, for example, while it allows for embedding files and data into specific color channels and bit planes, the user experience can be inconsistent.

- **File Embedding:** The tool struggled with embedding files despite offering this. For instance, I tried both a PDF and a word document and attempts to embed a PDF resulted in no data being retrieved, and embedding a .docx file produced incorrect hex output. This inconsistency makes it unreliable for embedding non-image files.
- **Image Quality:** The tool tends to bloat images, significantly increasing their file size, which could be undesirable if dealing with large batches or high-res images.
- **BlackWhite Image Embedding:**



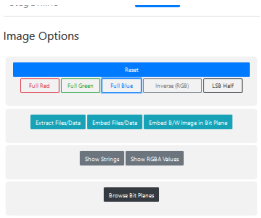
It successfully embedded a black and white image in the R0 bit plane, demonstrating ability to handle specific bit planes for embedding data, allowing for more control over the embedding process.

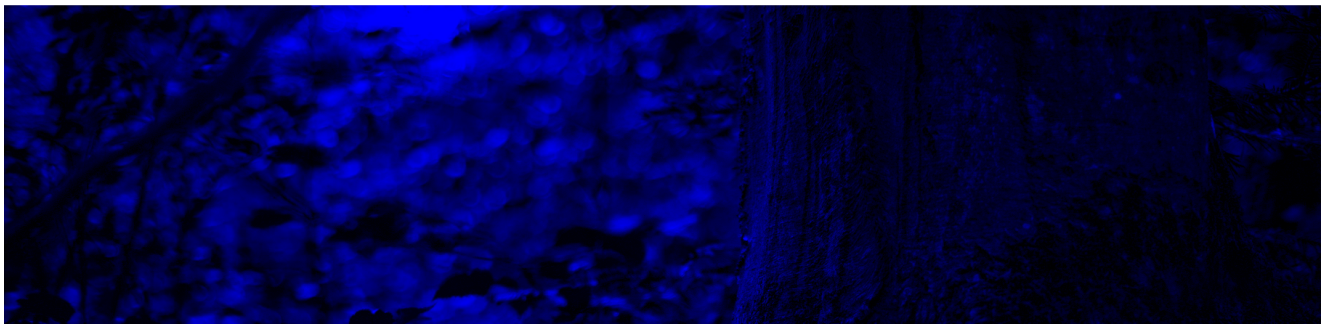
- **Customization:**



It offers more customisation options compared to stego.js.org, allowing users to select specific color channels and bit positions for embedding data, which can enhance subtlety and security of embedded data.

- **Useless Color Changer:**





Includes a feature to change colors (R, G, or B), invert colors, and apply LSB to half of the image. While these options might seem interesting, they do not add significant value to the steganography process and can be considered redundant.

Overall, georgeom.net/StegOnline provides a more feature rich experience but at the cost of reliability and ease of use. Advanced options might be useful for users who need more control over the embedding process, but tool inconsistencies and image bloating issues may be a deterring factor.

Benefits / Drawbacks Summary:

+ Allows for good control over bit placement.
+ Offers more advanced options such as embedding in other images or files.
- Very limited with documentation (e.g no tooltips) so features aren't obvious as to what they do.
- Struggled with some of its included features such as retreiving back encoded files.

1.4 Existing Algorithms

1.4.1 X Significant Bit (XSB)

After Note: After looking, I couldn't actually find anywhere online that offers an algorithm with this approach. I assumed it would due to being very similar to how LSB & MSB work.
The X Significant Bit (XSB) method is a variation of the traditional Least Significant Bit (LSB) and Most Significant Bit (MSB) techniques. Instead of modifying only the least significant bit of each pixel, XSB allows for the modification of any specified bit position within the pixel values, offering greater flexibility and control over the embedding process by allowing for a balance between data capacity and image quality.

XSB Steganography Process:

1. **Preparation:** Convert the secret data into binary format. This step ensures that the data can be easily embedded into the pixel values.
2. **Embedding:** Modify the specified bit position of each pixel value to embed the binary data. By choosing a specific bit position, the user can control trade-offs of data capacity and image quality.
3. **Marking End of Data:** Use a specific bit pattern to indicate the end of the embedded data. This helps in identifying where the embedded data ends during extraction.
4. **Extraction:** Retrieve the specified bit position from each pixel value and reassemble the binary data. This step reverses the embedding process to recover the hidden data.

Benefits / Drawbacks:

+ Provides flexibility in choosing the bit position for embedding, allowing for a trade-off between data capacity and image quality.

+ Can embed more data compared to traditional LSB by using higher bit positions.
- Higher bit positions may result in more noticeable changes to the image.
- Vulnerable to image processing operations that can alter the specified bit positions.

Comparison with Other Algorithms:

- **LSB:** XSB is an extension of LSB, providing more flexibility by allowing the modification of any bit position. This can increase data capacity but may also make changes more noticeable.
- **PVD:** XSB is simpler to implement compared to PVD, but PVD can embed more data in areas with larger pixel value differences, making it less noticeable.
- **F5:** XSB is less secure and robust compared to F5, which uses matrix encoding and permutation to distribute data across the image.

Classroom Demonstration: XSB is particularly advantageous for classroom demonstrations because it can be easily adjusted to show the effects of steganography. By using the most significant bit, changes in the image become more noticeable, making it easier for students to see how data is embedded. Conversely, using the least significant bit makes the changes less noticeable, demonstrating the subtlety of steganography.

1.4.2 Pixel Value Differencing (PVD)

Pixel Value Differencing (PVD) is a technique that uses the differences between pixel values to embed secret data. The method divides the image into non-overlapping blocks of two consecutive pixels and calculates the difference between their values. The difference value determines the number of bits that can be embedded in those pixels. Larger differences allow for more bits to be embedded, as they are less noticeable to the human eye.

PVD Steganography Process:

1. **Preparation:** Convert the secret data into binary format. This step ensures that the data can be easily embedded into the pixel values.
2. **Block Division:** Divide the image into non-overlapping blocks of two consecutive pixels. This allows for localised embedding based on pixel differences.
3. **Difference Calculation:** Calculate the difference between the pixel values in each block. The difference value determines the embedding capacity.
4. **Embedding:** Determine the number of bits to embed based on the difference value and modify the pixel values accordingly. This step ensures that larger differences can hide more data.
5. **Marking End of Data:** Use a specific bit pattern to indicate the end of the embedded data. This helps in identifying where the embedded data ends during extraction.
6. **Extraction:** Retrieve the embedded bits from the pixel values and reassemble the binary data. This step reverses the embedding process to recover the hidden data.

Benefits / Drawbacks:

+ Can embed more data in areas with larger pixel value differences, making it less noticeable.
+ More robust against image processing operations compared to LSB.
- Complexity increases with the need to calculate pixel differences and determine embedding capacity.
- May still be vulnerable to certain types of image processing operations.

Comparison with Other Algorithms:

- **LSB:** PVD is more robust and can embed more data compared to LSB, as it uses pixel differences to determine embedding capacity.
- **XSB:** PVD is more complex but can hide more data in areas with larger pixel value differences, making it less noticeable compared to XSB.
- **F5:** PVD is less secure and robust compared to F5, which uses matrix encoding and permutation to distribute data across the image.

1.4.3 F5

F5 uses matrix encoding to embed secret data into the cover image. It's designed to be more secure and robust compared to LSB and PVD. F5 also includes a permutation step to spread secret data across the image, making it more resistant to steganalysis.

Discrete Cosine Transform (DCT): The Discrete Cosine Transform (DCT) is a mathematical technique used to convert spatial domain data (pixel values) into frequency domain data. In the context of image processing, DCT is used to separate the image into parts of differing importance (frequencies). The lower frequencies represent the most significant parts of the image, while the higher frequencies represent finer details. By embedding data in the higher frequencies, the changes are less noticeable to the human eye.

F5 Steganography Process:

1. **Preparation:** Convert the image to the frequency domain using Discrete Cosine Transform (DCT). This step allows for embedding data in the frequency domain, which is less noticeable.
2. **Matrix Encoding:** Apply matrix encoding to embed the secret data into DCT coefficients. This step ensures that the data is embedded in a way that is less detectable.
3. **Permutation:** Permute DCT coefficients to distribute secret data across the image. This step increases the security of the embedded data.
4. **Inverse DCT:** Apply the inverse DCT to transform the image back to the spatial domain. This step converts the modified frequency domain image back to a regular image.
5. **Extraction:** Retrieve the embedded data by reversing the permutation and matrix encoding steps. This step recovers the hidden data from the image.

Benefits / Drawbacks:

+ Highly secure and robust against steganalysis.
+ Can embed a significant amount of data without noticeable changes to the image.
- More complex and computationally intensive compared to LSB and PVD.
- Requires conversion to and from the frequency domain, which can introduce artifacts.

Comparison with Other Algorithms:

- **LSB:** F5 is more secure and robust compared to LSB, as it uses matrix encoding and permutation to distribute data across the image.
- **XSB:** F5 is more complex but provides higher security and robustness compared to XSB.
- **PVD:** F5 is more secure and robust compared to PVD, as it uses matrix encoding and permutation to distribute data across the image.

1.5 Comparison of Encryption Methods

In this section, we will compare the different encryption methods available for use in the pixel steganography tool, focusing on their strengths and weaknesses to help determine the most suitable method for various scenarios.

1.5.1 AES (Advanced Encryption Standard)

AES is a widely used encryption standard known for its robustness and security. It operates on fixed block sizes and supports key sizes of 128, 192, and 256 bits. For this project, we will use AES in CBC (Cipher Block Chaining) mode with a 128-bit key and IV.

Benefits / Drawbacks:

+ High Security: AES is considered highly secure and is widely adopted in various industries.
+ Efficiency: AES is efficient in both software and hardware implementations, providing fast encryption and decryption.
+ Flexibility: Supports different key sizes, allowing for varying levels of security.

- Complexity: Implementing AES correctly and securely can be quite tricky, particularly with key management and padding schemes.
- Performance Overhead: While efficient, AES still introduces some performance overhead compared to simpler encryption methods.

1.5.2 Base64 Encoding

Base64 is a simple encoding scheme that converts binary data into ASCII text. It is not an encryption method but can be used for basic obfuscation of data.

Benefits / Drawbacks:

+ Simplicity: Easy to implement and understand, making it suitable for basic use cases.
+ Compatibility: Base64 encoded data can be easily transmitted over text-based protocols.
- Low Security: Base64 provides no real security and can be easily decoded.
- Increased Size: Encoded data is approximately 33% larger than the original binary data.

1.5.3 Custom Noise Addition

Custom noise addition involves adding random noise to the image to mask the steganographic changes. This method can be used with other encryption techniques to enhance security.

Benefits / Drawbacks:

+ Enhanced Security: Adding noise can make it more difficult for attackers to detect the presence of hidden data.
+ Flexibility: Noise levels can be adjusted to balance between security and image quality.
- Image Quality: High levels of noise can degrade the visual quality of the image.
- Complexity: Implementing effective noise addition requires careful tuning to avoid making changes too noticeable.

1.5.4 Choosing the Right Method

The choice of encryption method depends on the specific requirements of the use case:

- **High Security:** For scenarios requiring strong security, AES is the preferred choice due to its robustness and widespread adoption.
- **Basic Obfuscation:** For simple use cases where security is not a primary concern, Base64 encoding can be used for basic obfuscation.
- **Enhanced Stealth:** When the goal is to make the hidden data less detectable, custom noise addition can be used with other methods to help enhance security.

1.6 Interview

Third Party: Liam Cantle - Computer Science Teacher @ Exeter Mathematics School

1. **Question: How important is the user interface design for you in terms of ease of use and aesthetics? How far would you sacrifice user-friendliness for advanced features?**
   Answer: I would need the aesthetics to be clean, modern, and clear enough to use in a classroom setting. It should be both approachable and professional. There's definitely a balance to be struck between user-friendliness and advanced features, but I wouldn't sacrifice too much usability for the sake of additional advanced options. Ease of use would always remain a priority, especially if others are to learn or use it comfortably.
   Explanation: A visually appealing and intuitive interface is crucial to ensure that the tool is not overwhelming for users, especially in a classroom setting. While advanced features are appreciated, they shouldn't hinder the ability for everyone to use the software effortlessly. A clean design aids in understanding and trustworthiness.

2. **Question: What file types do you most commonly use? Would you rather specific file types be used?**
   Answer: I have no preference for file types, since most image files (JPG, PNG, BMP) would suit my needs. However, it would be good to support commonly used formats so that I don't have to waste time converting files.
   Explanation: Flexibility in file type support makes the tool more versatile and accessible, reducing potential friction for the user. While having no specific preference simplifies things, the convenience of supporting widely-used formats ensures usability in varied scenarios.

3. **Question: What level of data security do you expect and how much control do you want over the process (e.g., choosing from specific algorithms, adjusting parameters)?**
   Answer: It would be nice to have enough control to choose specific algorithms and adjust parameters when needed. For example, if you embed the data in the LSB (Least Significant Bit) of one of the colour channels, itd be interesting to evaluate how the image looks afterwarddoes embedding in a specific colour channel make the alteration more noticeable or not?
   Explanation: Security and control over processes are vital for understanding how data is embedded within the image and how the results compare visually. The ability to customise and test these parameters allows for experimentation and ensures the solution meets specific needs or preferences.

4. **Question: How important is batch processing to you?**
   Answer: Batch processing is not very important for me most of the time. However, it could be useful if embedding large amounts of data or working with multiple images simultaneously. In such cases, having this feature as an option would be valuable.
   Explanation: Although batch processing isnt an essential feature for every use case, having the option for high-volume scenarios increases the tools flexibility. Its particularly beneficial when efficiency in handling bulk tasks becomes a priority.

5. **Question: Should it attempt to downscale resolution to deal with high-res images quicker, or would you rather sacrifice speed for more accurate steg?**
   Answer: Downscaling the resolution would help reduce file size, which can be particularly useful when the image is sent as an attachment. It would also save time for processing, but I would still like it to retain reasonable accuracy. While its a nice-to-have feature, its not essential for the tool to include this.
   Explanation: Balancing speed and quality is significant in steganographic operations. Downscaling ensures responsiveness and lower memory usage, especially for large high-resolution images, making the process compact without significantly degrading quality.

6. **Question: Would you like the ability to preview the stego image before finalising the embedding process?**
   Answer: Yes, having a preview side-by-side with the original image would be extremely helpful, especially in a classroom situation. Itd be amazing if you could zoom in on both images simultaneously to see if the embedded changes are visible at a detailed level. This would make it easier to assess the quality of the steganography before committing to the final result.
   Explanation: Previews help visually validate the embedding process and enhance user confidence in the result. The ability to compare side-by-side and zoom in synchronously is particularly useful in educational scenarios where understanding nuances and visual differences is critical.

7. **Question: Would you find a save configuration system useful for reusing settings across multiple sessions?**
   Answer: That would be quite useful for streamlining workflows over multiple sessions. Being able to save and load configurations for quick application would save time, especially for frequently used settings. But if it isnt there, it wouldnt be a major concern.
   Explanation: A save configuration system can enhance user experience by reducing repetitive setup steps. While not essential, its a convenience feature that improves efficiency for repeated or lengthy projects.

8. **Question: Would you find it useful to have a detailed log of all steganography and conversion operations performed? What would you want contained in this if yes?**
   Answer: I wouldn't mind if the feature was present or not, as I wouldn't use it often. However, if you include it, a toggle to turn the logging on or off would be great. For example, "Anonymous mode" could disable logs, ensuring some privacy during the process.
   Explanation: Detailed logs can assist in debugging or reviewing actions for advanced users but may not

be applicable to all. Allowing users to decide whether logs are recorded balances functionality with privacy preferences, making the tool more inclusive.

9. **Question: Are there any specific accessibility features you require (e.g., keyboard navigation)?**
   Answer: Keyboard navigation would certainly be nice to have, especially for improving efficiency, but its not something I would consider essential. As long as the interface remains intuitive and doesnt require too many clicks, accessibility wont be a big issue for me.
   Explanation: Accessibility features like keyboard navigation improve usability for advanced users or those with specific needs. Though not a necessity here, its inclusion could broaden the tool's appeal and increase productivity.

1.7 Interview Review

The interview with Liam Cantle provided valuable insights that directly inform the project objectives:

- Liam emphasised the importance of a "clean, modern, and clear" interface suitable for classroom use, stating that user-friendliness should not be sacrificed for advanced features. This will strongly be taken into account, implementing more complex functionality in a simple to use way (e.g., a tabbed interface design with clear visual feedback). His request for a side-by-side image preview with synchronised zooming capability will also be a necessary objective.
- While expressing no strong preference for specific file types, Liam indicated the importance of supporting commonly used formats to avoid conversion overhead, suggesting inclusion of comprehensive image format support (PNG, JPG, BMP) would be useful to include. His comment about downscaling being "nice-to-have" suggests it's an optional extra so shouldn't be seen in core features, but the software should implement efficient resize operations.
- Liam's interest in having control over algorithm selection and parameters will result in support for multiple embedding techniques with configurable parameters.
- While Liam considered configuration saving as useful but not critical, it can seriously enhance workflow efficiency, particularly for repeated operations.
- Liam's feedback about processing speed versus accuracy trade-offs will influence performance objectives, particularly in implementing efficient pixel manipulation operations while maintaining quality. His comment about preview functionality necessitated robust real-time processing capabilities.
- Throughout the interview, Liam emphasised the tool's educational potential, particularly evident in his desire for visual comparisons and parameter experimentation. This will influence the decision to include comprehensive visual feedback and detailed configuration options in the objectives.

1.8 Objectives

The goal of this project is to create an easy-to-use pixel steganography tool to show how it is used in classroom environments.

1. **User Interface & Experience**
   (a) Design a tabbed interface with at least 4 functional tabs (encoding, decoding, configuration, conversion) with 100% navigation between them
   (b) Provide real-time preview with zoom functionality supporting at least 200% magnification and sub-pixel inspection
   (c) Implement file explorer browse handling with support for at least 3 common image formats
   (d) Offer clipboard integration with <100ms response time for text operations
   (e) Enable configuration management through visual interface with real-time JSON preview updates
   (f) Provide immediate visual feedback for operations with progress bars accurate to within ś5% of actual task completion
2. **Steganography Implementation**
   (a) Support multiple embedding techniques:

   i. X Significant Bit (XSB) with at least 8 configurable bit positions (1-8)
   ii. Pixel Value Differencing (PVD) with adaptive capacity of at least 2-4 bits per pixel based on image characteristics
   (b) Implement robust data extraction with at least 99.5% accuracy for embedded data retrieval
   (c) Use end markers for reliable data detection with zero false positives
   (d) Add configurable noise from 1-10 levels to mask steganographic changes
   (e) Provide real-time preview of original vs stego images with <500ms update time

3. **Encryption & Security**
   (a) Implement multiple encryption methods:
      i. AES (CBC mode) with 128-bit key/IV support and 100ms processing time for texts up to 10KB
      ii. Base64 encoding for basic protection with zero character corruption
      iii. Custom noise addition with at least 5 measurable levels for visual security
   (b) Support full Galois Field implementation for AES:
      i. Dynamic SBox generation with 256-entry tables
      ii. Custom matrix operations with 100% mathematical correctness
      iii. CBC mode implementation with full 128-bit block chaining
   (c) Validate encryption parameters (16-byte key length, 16-byte IV requirements) with 100% rejection of invalid inputs

4. **Configuration Management**
   (a) Support JSON-based configuration files:
      i. Algorithm selection (XSB/PVD) with 100% validation
      ii. Encryption method selection with at least 3 options
      iii. Custom parameters with at least 5 configurable fields
   (b) Implement configuration validation:
      i. Required parameter checking with 100% coverage of critical fields
      ii. Algorithm-specific validation with meaningful error messages for all potential issues
      iii. Encryption parameter validation with zero unhandled exceptions
   (c) Enable save/load of configurations with <50ms file operations
   (d) Provide visual configuration generation with real-time feedback on parameter changes

5. **Image Processing & Conversion**
   (a) Support at least 3 image formats (PNG, JPG, BMP) with 100% compatibility
   (b) Implement batch processing capabilities:
      i. Bulk format conversion of at least 10 files per operation
      ii. Resize operations maintaining aspect ratio within 0.1% tolerance
      iii. Quality control for lossy formats with at least 10 adjustable levels
   (c) Use efficient data structures:
      i. LinkedList for task management with O(1) insertion time
      ii. Merge sort for file ordering with O(n log n) efficiency
   (d) Handle aspect ratio preservation with <0.5% distortion
   (e) Implement file collision prevention with 100% unique filenames

6. **Performance & Resource Management**
   (a) Optimise pixel manipulation operations:
      i. Efficient matrix operations with <20ms processing time per 100x100 pixel block
      ii. In-place image modifications to reduce memory usage by at least 50% compared to copy-modify approach

iii. Maintain memory overhead below 2x the size of the original image during processing

(b) Implement progress tracking:

i. Task queue management with 100% completion reporting
ii. Visual progress indicators updating at minimum 10Hz refresh rate
iii. Status updates with <100ms latency

(c) Provide error handling and recovery:

i. Input validation with 100% coverage of edge cases
ii. Operation validation with specific error codes for at least 10 common failure scenarios
iii. Error feedback with user-friendly messages in 100% of error cases

1.9 Limitations

1. **Supported Formats:**
   - The application will only be feasible if supporting the most common image file formats (e.g., JPG, PNG). This may exclude less common or proprietary formats, limiting its adaptability to niche use cases.
   - Users needing support for unsupported formats must convert their files using external tools, which may introduce security risks if performed on untrusted platforms.
2. **Embedding Constraints:**
   - Lossy formats such as JPEG can struggle with data integrity during the embedding process, often introducing artifacts that may affect the overall quality of the steganographic image.
   - Lossless formats, like PNG, are generally better suited for steganography but produce larger file sizes, which could pose a challenge in scenarios with storage or bandwidth limitations.
3. **Alteration Threshold:**
   - Excessive data embedding can lead to noticeable visual distortions or even corruption of the image, compromising both usability and subtlety.
   - To ensure balance, limits must be enforced to preserve quality and integrity of cover media while embedding data.
4. **Performance Limitations:**
   - Depending on programming language used, it could be more simple to code, but come at the cost of worse performance.
   - Critical sections might require optimisation or a hybrid implementation with more efficient languages, depending on future requirements.
5. **Processing Performance:**
   - Limited computational resources can increase processing time, potentially making the tool feel 'unusable' on devices with constrained hardware specifications.
6. **Algorithmic Trade-offs:**
   - Chosen steganography algorithms might not be optimal for every use case, requiring users to explore alternatives or adjust parameters for specific scenarios.
   - Experimentation with different algorithms may demand additional time and effort from users to achieve desired results.
7. **Hash Table Issues:**
   - Hash tables can encounter challenges such as memory consumption and collision risks, which must be carefully managed.
   - Suboptimal hash table implementations may lead to performance issues, particularly when handling large datasets or high-resolution images.

8. **Embedding Methodology:**
    - While hashing techniques are employed for data integrity and watermarking, they are not immune to vulnerabilities like collisions or attacks, reducing their effectiveness under advanced steganalysis methods.
    - Users should be aware of the limitations of these techniques and their potential weaknesses in certain scenarios.
9. **Matrix Operations Optimisation:**
    - Efficient matrix operations are pivotal for pixel-level manipulations in image processing. Inefficiencies here can significantly impact computational load and processing times.
    - Processing high-resolution images may expose performance bottlenecks if matrix operations are not thoroughly optimised.
10. **Dynamic GUI Elements:**
    - Dynamically creating objects in the GUI introduces challenges in maintaining a responsive and seamless user experience.
    - Poor implementation can result in a slow or unresponsive interface, detracting from usability and user satisfaction.
11. **Storage and Capacity Considerations:**
    - The application has a finite capacity for embedding data, determined by the size and format of the cover image, making it unsuitable for embedding large or unlimited content.
    - Users must remain mindful of these constraints and adjust the volume of data to embed accordingly, ensuring the integrity of the image is preserved.

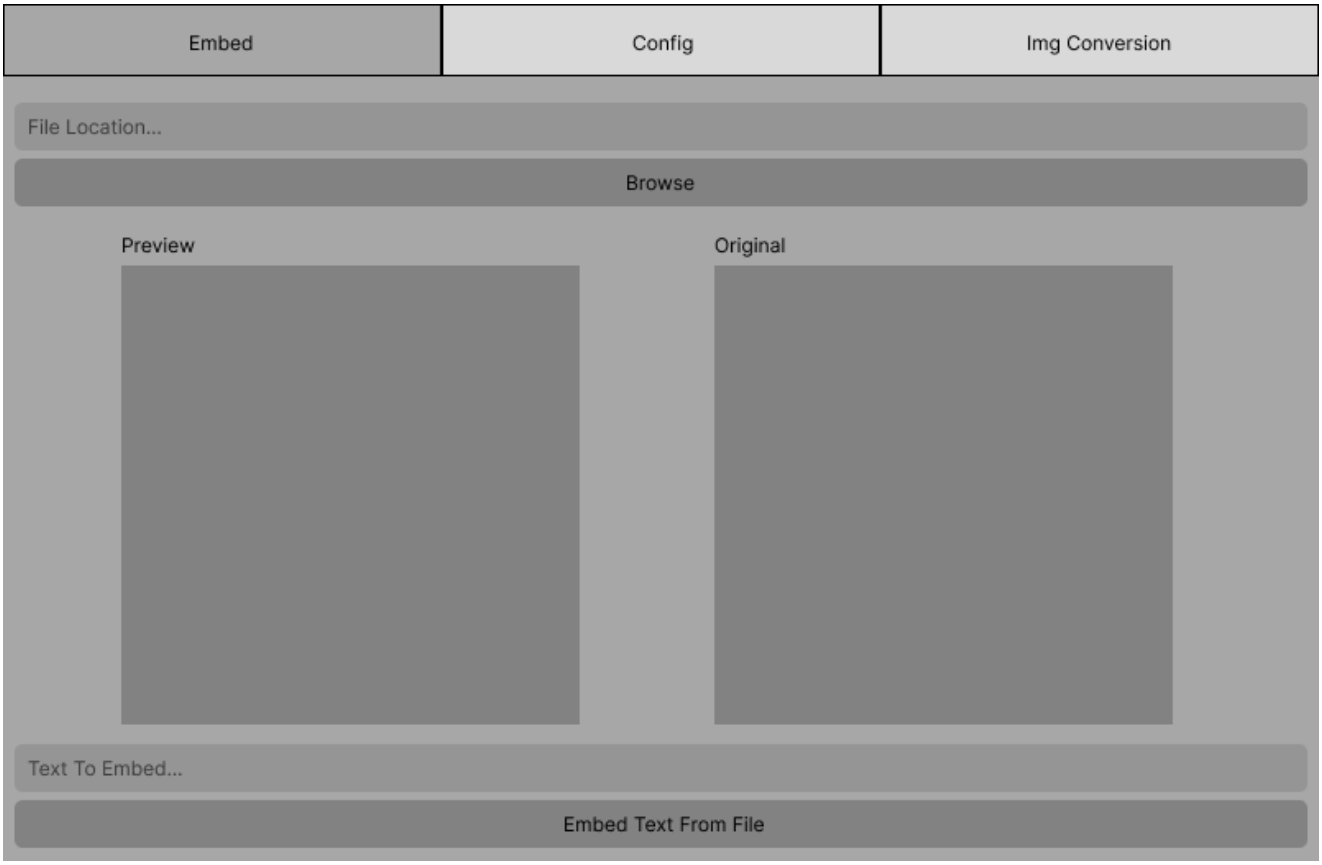
1.10 Key Definitions

1. **Cover Image:** The original, unaltered image that serves as the medium for embedding the secret data. Its integrity and appearance should ideally remain unchanged after embedding.
2. **Stego Image:** The resulting image after the payload (hidden data) has been embedded within the cover image. The stego image should appear indistinguishable from the cover image to prevent detection.
3. **Payload:** The secret data or message that is to be embedded within the cover image. This can include text, binary data, or other types of encoded information.
4. **Embedding:** The algorithmic process of encoding the payload into the cover image in such a way that the modifications remain imperceptible to a casual observer.
5. **Extraction:** The inverse of embedding; it is the process of decoding and retrieving the hidden payload from a stego image.
6. **Steganalysis:** The analytical process or techniques used to detect the presence of hidden data within a stego image. This includes methods for identifying irregularities introduced during embedding.
7. **Redundant Data:** Data or pixel components within the cover image that can be altered without noticeably affecting its visual quality or usability. Redundant data is critical for embedding the payload while maintaining image fidelity.
8. **Noise:** Variations or imperfections in the cover image's signal that can either mask the changes introduced by embedding or be utilised directly for hiding data. Noise can function as a natural carrier for hidden information.
9. **Capacity:** The maximum amount of data that can be stored within the cover image while maintaining perceptual indistinguishability. This depends on the image format, resolution, and embedding algorithm.
10. **Robustness:** The ability of the stego image to preserve the hidden payload under various transformations or modifications, such as resizing, compression, or other image processing techniques.

11. **Perceptibility:** The extent to which the embedding process alters the cover image. A high level of imperceptibility ensures that any modifications remain unnoticed by human observers or basic analytical methods.
12. **Lossy Formats:** Image formats, such as JPEG, that use compression algorithms that discard some data to reduce file size. These formats introduce challenges for embedding secret data, as embedded payloads may degrade or become corrupted during compression.
13. **Lossless Formats:** Image formats, such as PNG or BMP, that preserve all original data without compression artifacts. These formats are generally preferred for embedding payloads due to their higher fidelity and reliability.
14. **Hashing:** A cryptographic technique used to ensure data integrity during embedding and extraction. It can be used to validate the payload but has limitations, such as vulnerability to collisions.
15. **Embedding Algorithm:** The specific method or set of instructions used to encode and hide the payload within the cover image. It defines the trade-offs between capacity, robustness, and perceptibility.
16. **Pixel Manipulation:** The process of altering pixel values within the cover image to encode data. This may involve adjusting color channels, least significant bits (LSB), or other image properties.
17. **Matrix Operations:** Mathematical operations performed on image data represented as pixel matrices. These are used for efficient manipulation and embedding during the steganographic process.

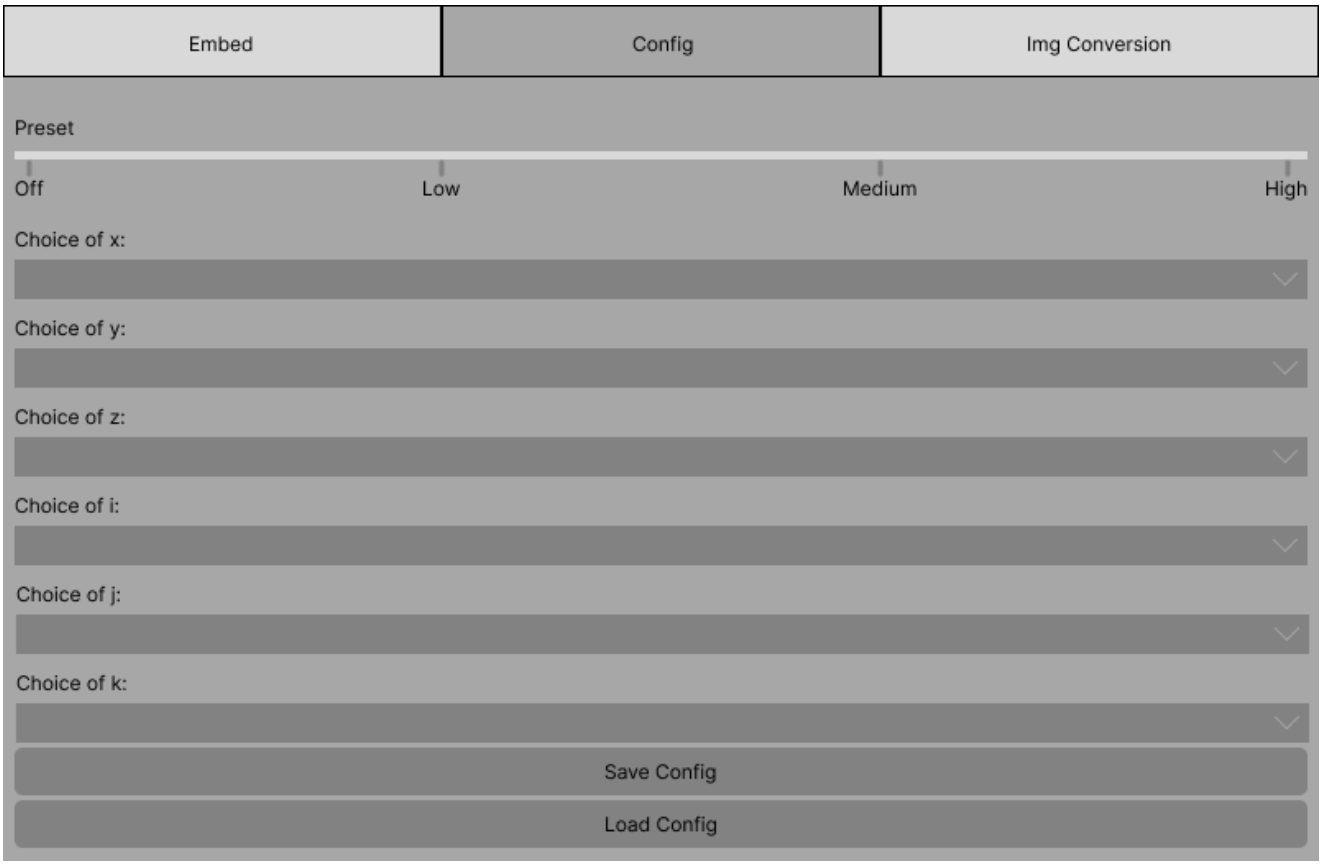
1.11 Prototype

1.11.1 Main Page



This page is designed to allow users to embed text or data into an image. Users can select an image file from their local storage using the "Browse" button, and the location of the file will be shown under "File Location." A preview of the selected image will be available on the left, while the original unmodified image is displayed on the right. Users can input the text they want to hide inside the image manually in the "Text to Embed" box, or they can select a text file for embedding by clicking "Embed Text from File." Once the data is embedded, the modified image can be saved or further processed. This page provides a simple, intuitive workflow for embedding information into images, making the concept of pixel steganography more accessible.

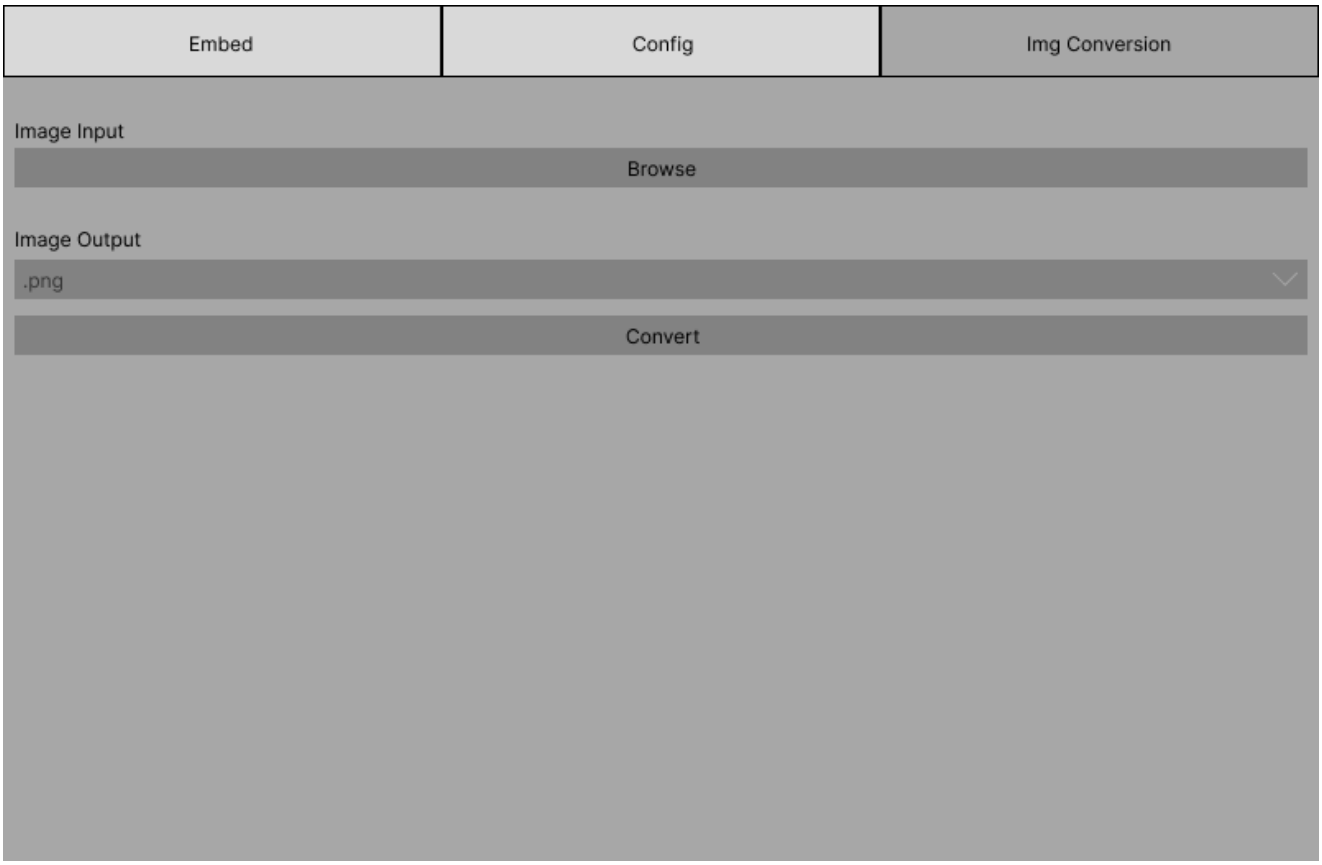
1.11.2 Configuration Page



This is the core page where users can control and fine-tune the steganography process. It provides various options for users to select encoding settings, allowing for more precise control over how the data is embedded in the image. At the top, a Preset slider offers different levels of encoding complexity (Low, Medium, High), which corresponds to how much information can be hidden versus how much the image's visual fidelity is preserved.

Below the preset slider, there are multiple dropdown menus (labelled Choice of x, y, z, f, j, k) allowing users to configure specific variables related to the steganography algorithm, such as how the data is distributed across pixel colour channels or how it interacts with the image format. This page also allows users to save or load custom configurations via the Save Config and Load Config buttons. This flexibility is ideal for both classroom demonstrations and advanced users who wish to experiment with different encoding techniques. The detailed customisation ensures that users can experiment with the trade-off between image quality and the amount of hidden data.

1.11.3 Image Conversion



The purpose of this page is straightforward, allowing users to convert images between different formats; the user browses for an input image using the 'Image Input' and then selects the desired output format from a dropdown (such as to PNG or JPG). Once the appropriate format is chosen, users click the Convert button to transform the image. This page provides essential functionality that supplements the embedding process, as certain steganography techniques may work better with specific image formats, and users can easily switch between them without needing to rely on external software. The design is simple but serves a crucial purpose in ensuring compatibility with the steganography tool.

2 Documented Design

2.1 Design Overview

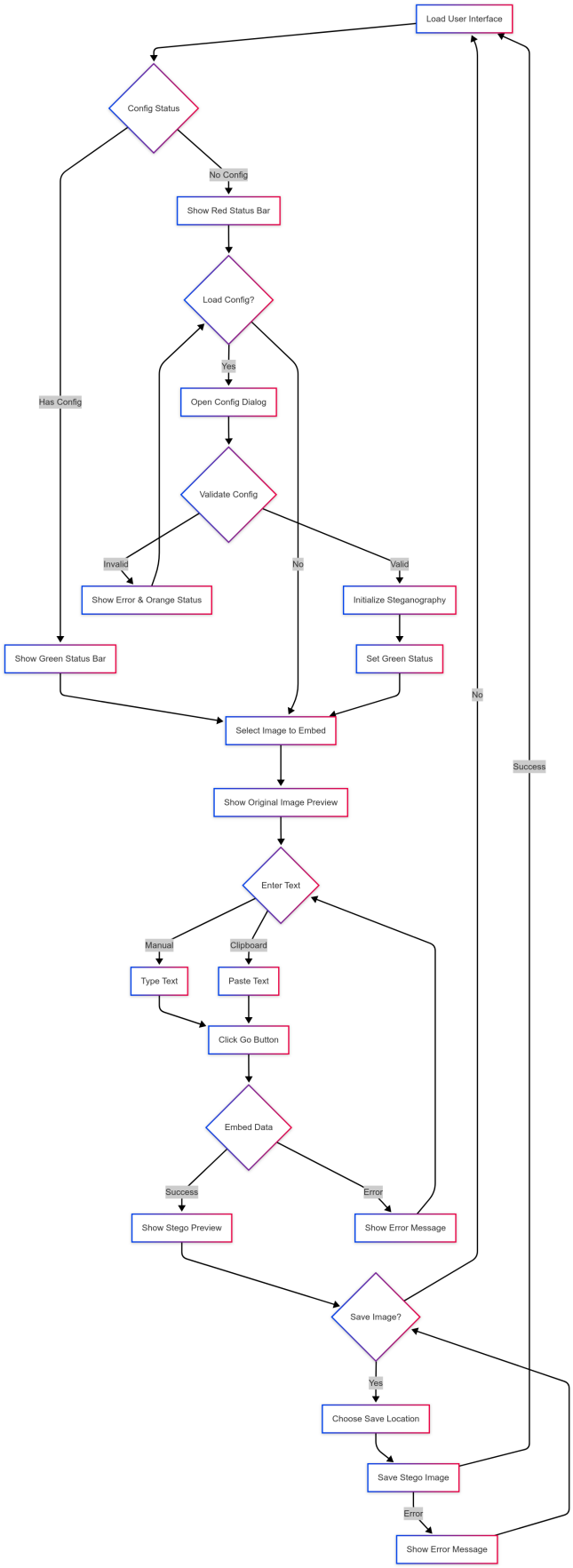
The application is going to be an image-based steganography tool that enables users to securely embed and extract secret data (payloads) within image files, while maintaining optimal balance between capacity, robustness, and perceptibility. The end result of the application should streamline image processing, matrix manipulation, and cryptographic operations. Below is an overview of its key components and how they interact to achieve the desired outcomes.

1. **Core Functionalities:**
    - **Data Embedding:** Allows the user to embed a specified payload within a cover image, producing a stego image. This process is performed efficiently, ensuring minimal perceptual changes in the image.
    - **Data Extraction:** Provides the ability to retrieve embedded payloads from a stego image, ensuring data integrity and accuracy during extraction.
    - **Image Format Handling:** The application supports common lossless and lossy formats like PNG and JPEG, leveraging available third-party libraries for image decoding and manipulation.
    - **Validation and Integrity Checks:** Ensures the payload remains intact and verifiable during embedding and extraction through hashing techniques or equivalent validation mechanisms.

2. **Third-Party Dependencies:**
    - **PIL/Pillow Library:** Used for handling image input and output, as well as performing operations like resizing, format conversion, and pixel manipulation.
    - **PyQt6/UI Library** Used to provide users with an intuitive interface for upload, embedding, and extraction processes.
    - **Pyperclip/Clipboard Library** Used to copy text to the clipboard
3. **Operational Workflow:**
    - **Step 1: Input Handling -** The user provides the application with a cover image and the payload (e.g., text or binary data). The file type and size are validated to ensure compatibility with the embedding algorithm.
    - **Step 2: Embedding Process -** The payload is embedded into the cover image using a customisable algorithm (e.g., Xth Significant Bit (XSB) manipulation or equivalent methods). Any redundant data within the cover image is carefully edited to accommodate the payload while maintaining imperceptibility.
    - **Step 3: Output Generation -** A stego image is generated and saved, retaining the original image properties while discreetly containing the hidden payload.
    - **Step 4: Extraction Process -** Users select a stego image, and the application performs the necessary decoding to extract the hidden payload. Validation checks are performed to ensure the payload matches its original integrity (e.g., through hash verification).

2.2 Embedding & Decoding Pages

2.2.0.1 Flowchart for the embedding page

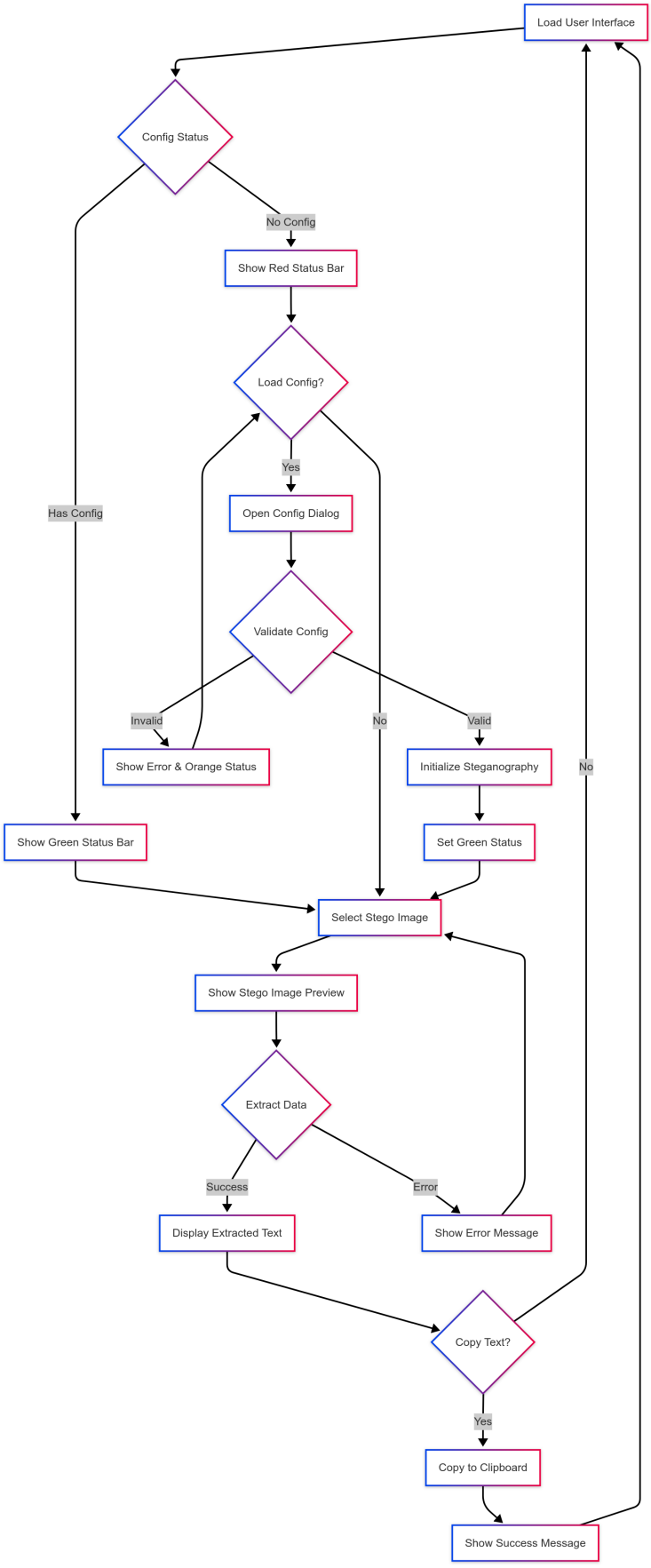


The flowchart illustrates the process of embedding data into an image using steganography. The procedure begins with the loading of the user interface, followed by a check on the configuration status. If no configuration is detected, a red status bar is displayed, and the user is prompted to load a configuration file. If a configuration is available, it is validated. An invalid configuration results in an error message and an orange status bar, whereas a valid configuration initiates the steganography process, setting a green status.

Once the configuration is successfully validated, the user selects an image to embed data into, which is then previewed. At this stage, the user enters the text to be embedded, either by typing manually or pasting from the clipboard. After confirming the input, the system attempts to embed the data within the selected image. If the embedding process is successful, a preview of the steganographic image is displayed. However, if an error occurs, an appropriate error message is shown.

Following the successful embedding of data, the user is given the option to save the steganographic image. If they choose to do so, a save location must be specified before the image is stored. In the event of a failure during the saving process, an error message is displayed, allowing the user to take corrective action. This structured workflow ensures a clear and systematic approach to embedding and saving hidden data within an image while providing appropriate feedback and error handling at each stage.

2.2.0.2 Flowchart for the decoding page

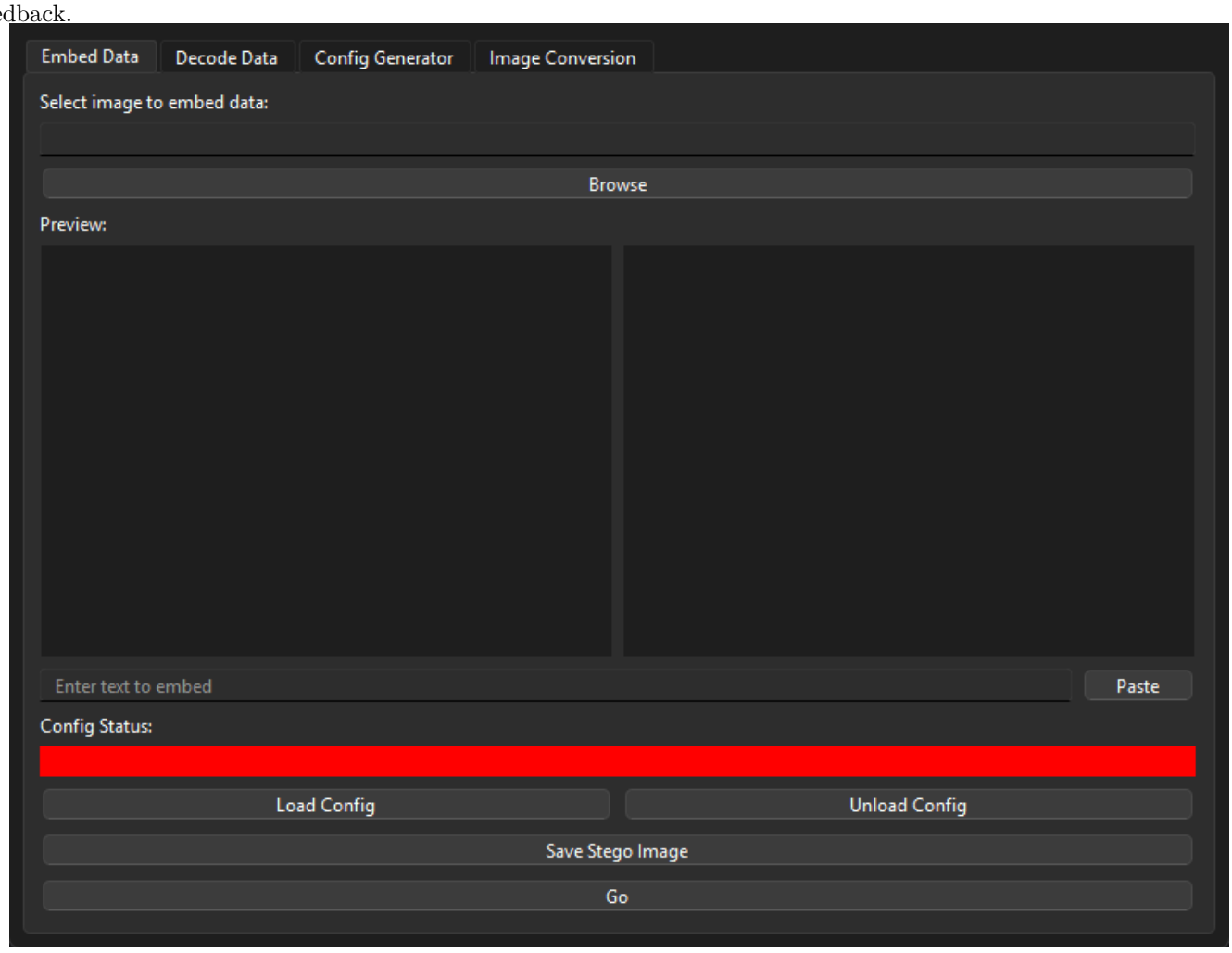


The flowchart outlines the process of extracting hidden data from a steganographic image. The procedure

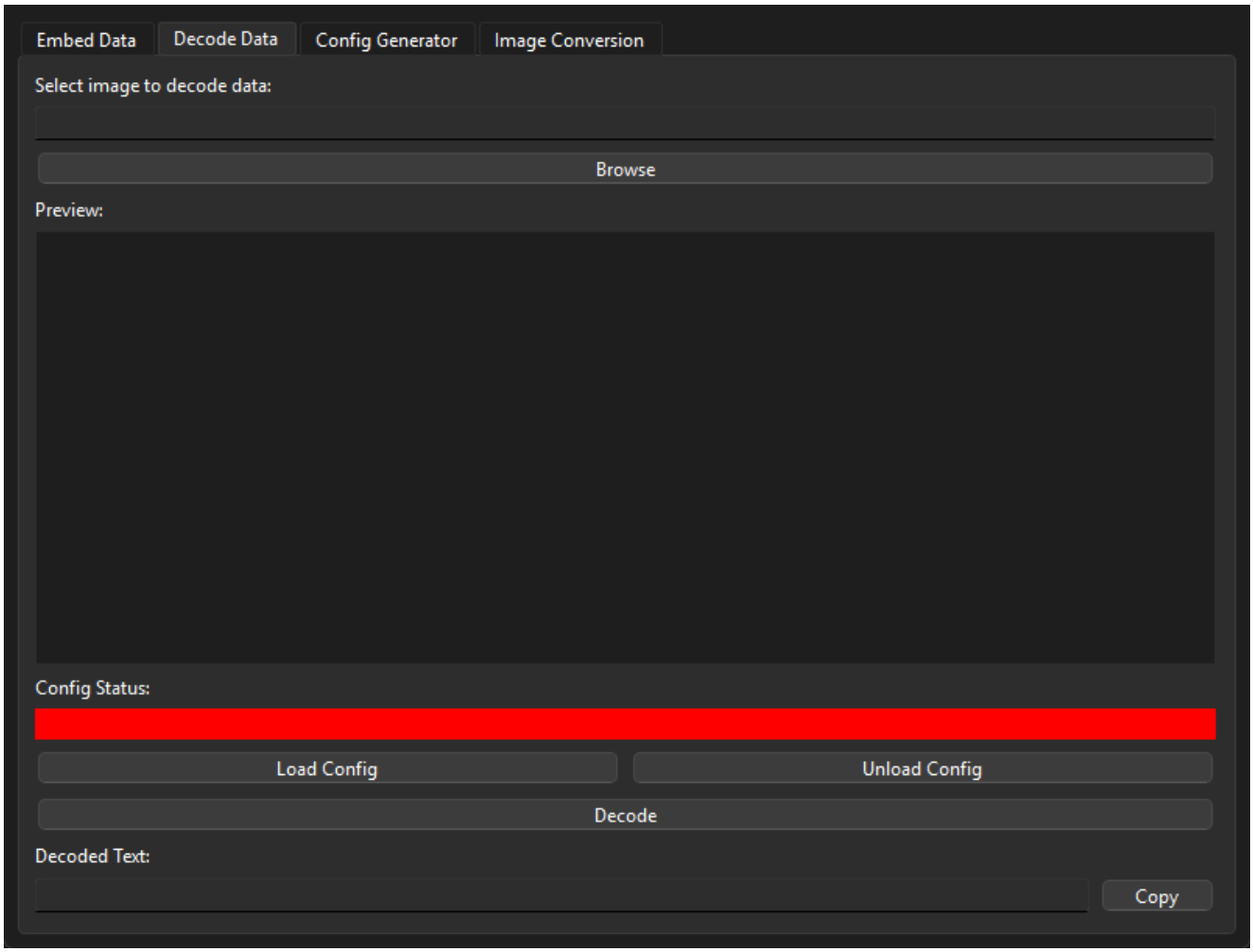
begins with the loading of the user interface, followed by a check on the configuration status. If no configuration is found, a red status bar is displayed, and the user is prompted to load a configuration file. If a configuration is available, it is validated. An invalid configuration results in an error message and an orange status bar, whereas a valid configuration initiates the steganography process and sets a green status.

Once the configuration is validated, the user selects a steganographic image, which is then previewed. The system attempts to extract the embedded data. If extraction is successful, the hidden text is displayed. If an error occurs during extraction, an appropriate error message is shown.

Following the successful extraction of data, the user is given the option to copy the extracted text to the clipboard. If they choose to do so, the text is copied, and a success message is displayed. This structured workflow ensures a systematic approach to retrieving hidden data while incorporating appropriate error handling and user feedback.



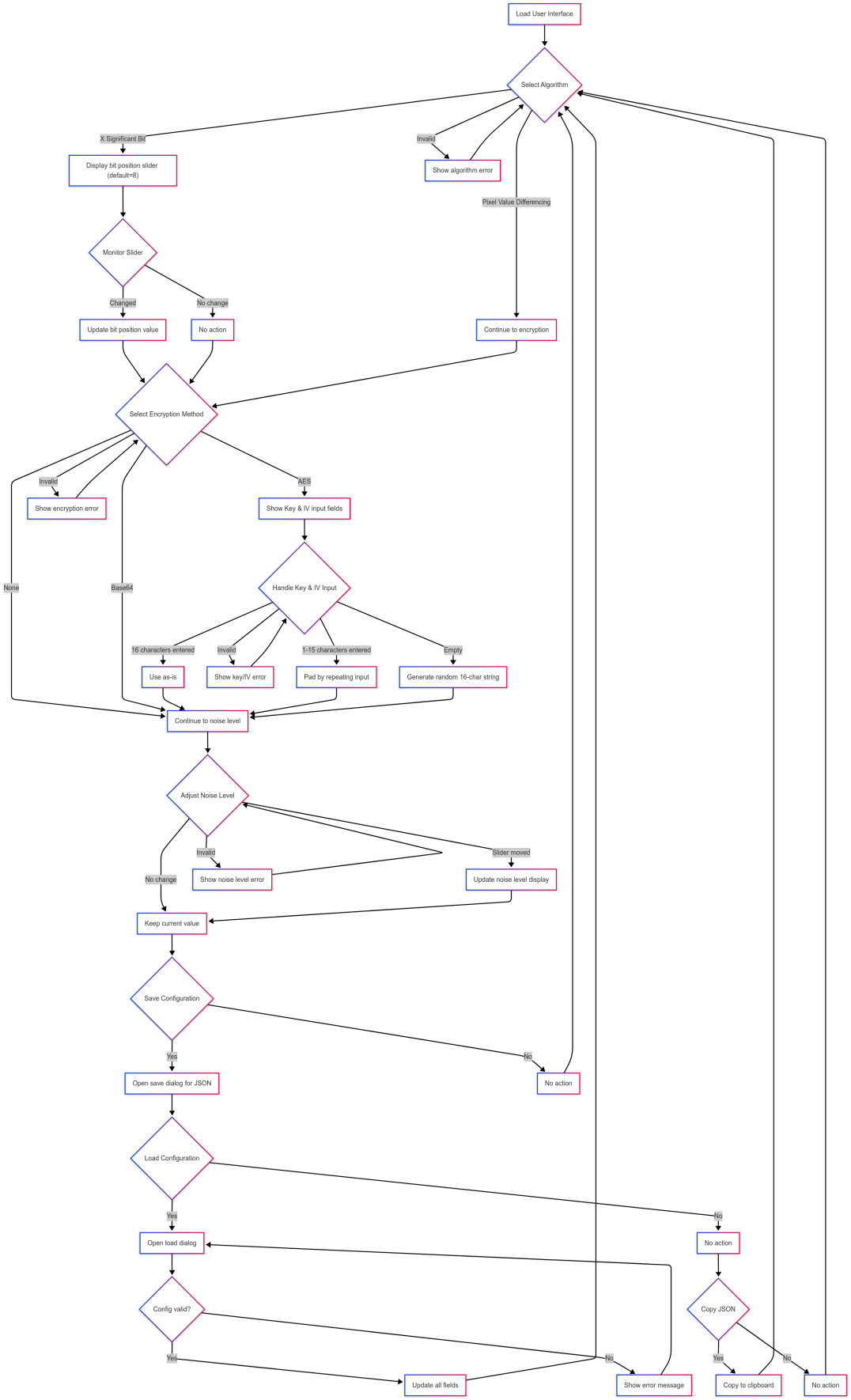
This design keeps things very straightforward for the actual embedding process, making it clear what is required from a glance. The browse button uses the default file explorer of the system, so helps with ease of use since it's what the user is actually used to. 'Paste' automatically inputs what is copied to your current clipboard into the text box. Load config also uses file explorer with it set to filter just JSONs. Unload is pretty self-explanatory and will clear what is saved as the present configuration. Save will also run and show the preview whilst opening file explorer for the user to choose where to save their image to. Go only runs it and shows the preview without offering to save. All options also have hoverable tooltips.



This has the same layout as the embed data page with the exception that the text box cannot be typed in, and it has a 'Copy' to clipboard button.

2.3 Configuration Page

2.3.0.1 Flowchart for the configuration page



The flowchart details the encryption configuration process within a steganographic system. It begins with loading the user interface, followed by the selection of an encryption algorithm. If an invalid algorithm is chosen, an error message is displayed; otherwise, the process continues to encryption.

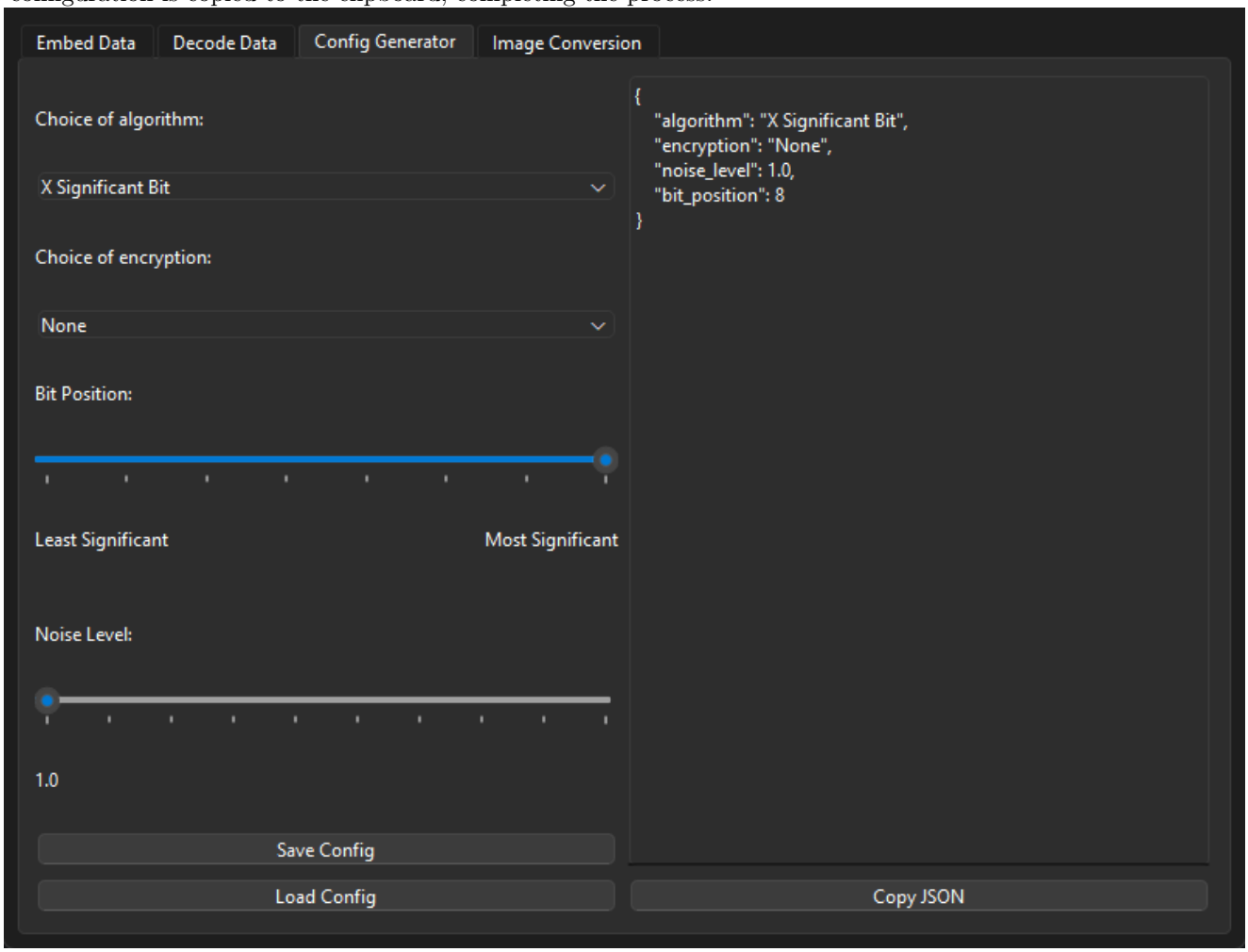
If the chosen method requires bit-plane selection, a position slider is displayed, allowing the user to adjust the significance level. Changes to the slider update the bit position value dynamically, while no changes result in no action. The next step involves selecting the encryption method. If an invalid method is chosen, an error message appears. If Advanced Encryption Standard (AES) is selected, input fields for the encryption key and initialisation vector (IV) are displayed.

The user then provides key and IV inputs. If the input is exactly 16 characters, it is used as is. If it is between 1 and 15 characters, the input is padded to 16 characters. If left empty, a random 16-character string is generated. Invalid input results in an error. Once valid input is provided, the process moves to noise level adjustment.

The noise level can be manually adjusted or left unchanged. If invalid values are entered, an error is displayed. If adjusted, the noise display updates accordingly.

After setting the encryption parameters, the user can save the configuration. If confirmed, a save dialog appears to store the configuration as a JSON file. The configuration can later be loaded, at which point its validity is checked. If invalid, an error is displayed; if valid, all fields are updated.

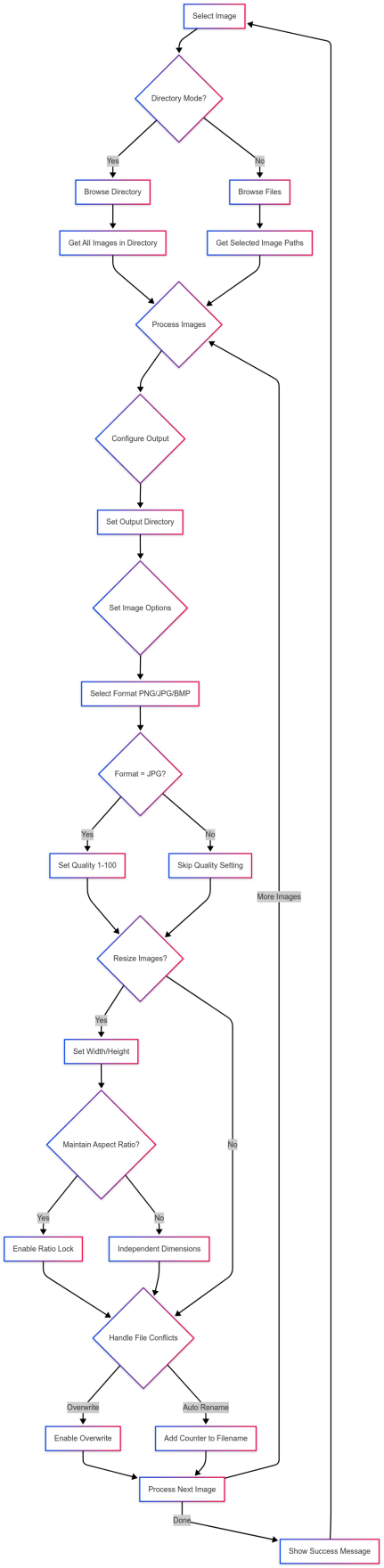
Finally, the user can copy the JSON configuration. If an error occurs, an error message is shown. If successful, the configuration is copied to the clipboard, completing the process.



One of the first things noticeable on this page is the live JSON display. It dynamically changes based on options that the user has chosen and allows for it to be copied to clipboard in case the user wants to easily be able to see how configurations are saved, or want to send their config in text form easily. I decided it would be best not to allow in the edits in the config viewer since it really isn't necessary (due to the ease of customisation on the left) and could result in odd behaviour. The bit position and noise level are easy to use sliders since it allows for specific choices in a user-friendly way rather than just a spinbox.

2.4 Image Conversion Page

2.4.0.1 Flowchart for the image conversion page



Query successful

Okay, here's a flowchart description based on the provided text:

The flowchart outlines the image conversion process. It begins with the user selecting an image. The system then checks if directory mode is enabled.

If directory mode is active, the system browses the directory and retrieves all images within. If not, the system browses for specific files and gets the selected image paths.

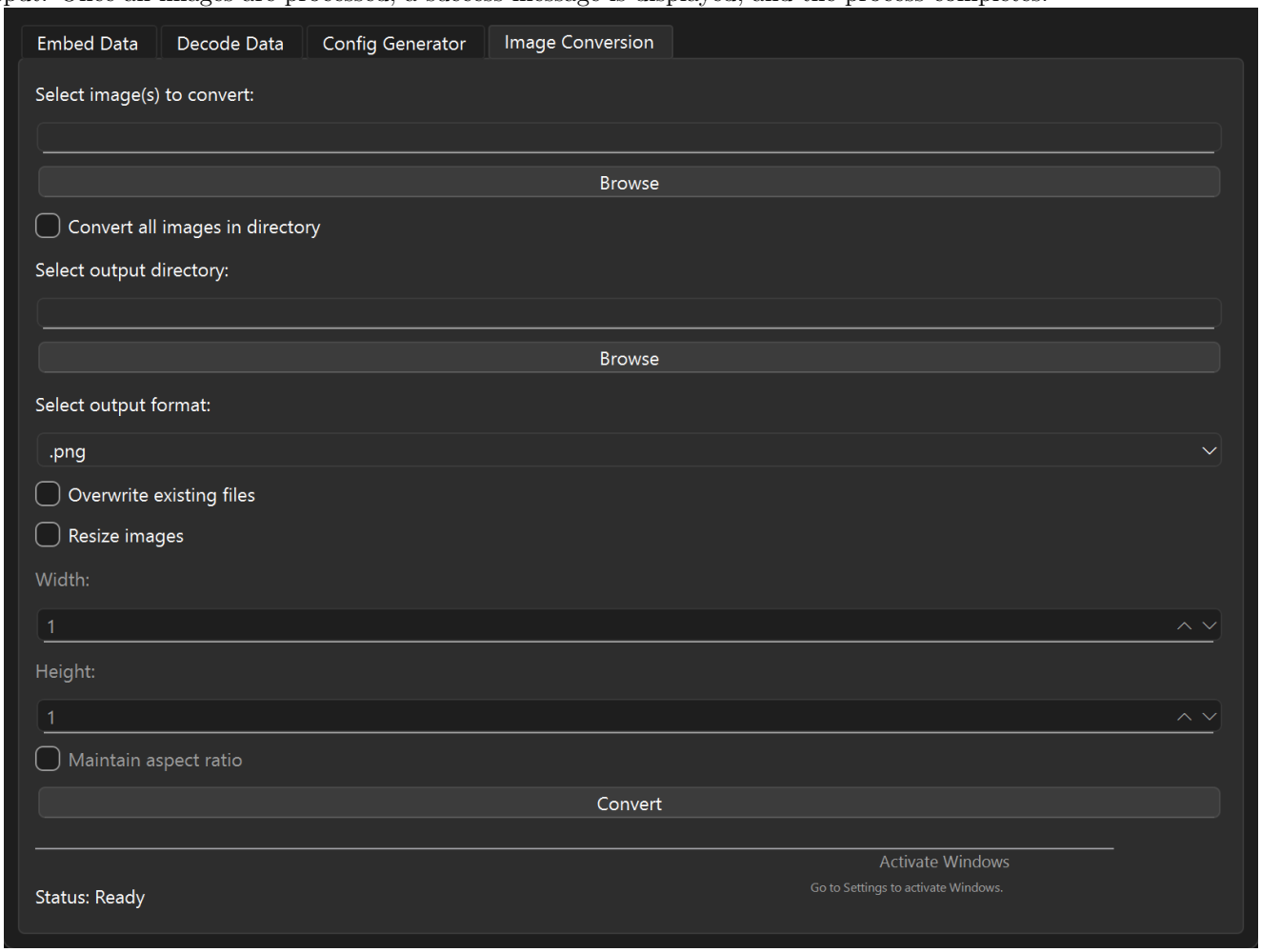
The process continues with configuring the output. The user sets the output directory and then configures image options. This involves selecting the output format: PNG, JPG, or BMP.

If JPG format is selected, the user is prompted to set the quality level, ranging from 1 to 100. If another format is selected, this step is skipped.

The user is then asked if images should be resized. If yes, the user sets the desired width and height. Following this, the system checks if the aspect ratio should be maintained. If maintained, ratio lock is enabled; otherwise, dimensions are treated independently.

The system then handles potential file conflicts. The user can choose to overwrite existing files or automatically rename new files by adding a counter to the filename.

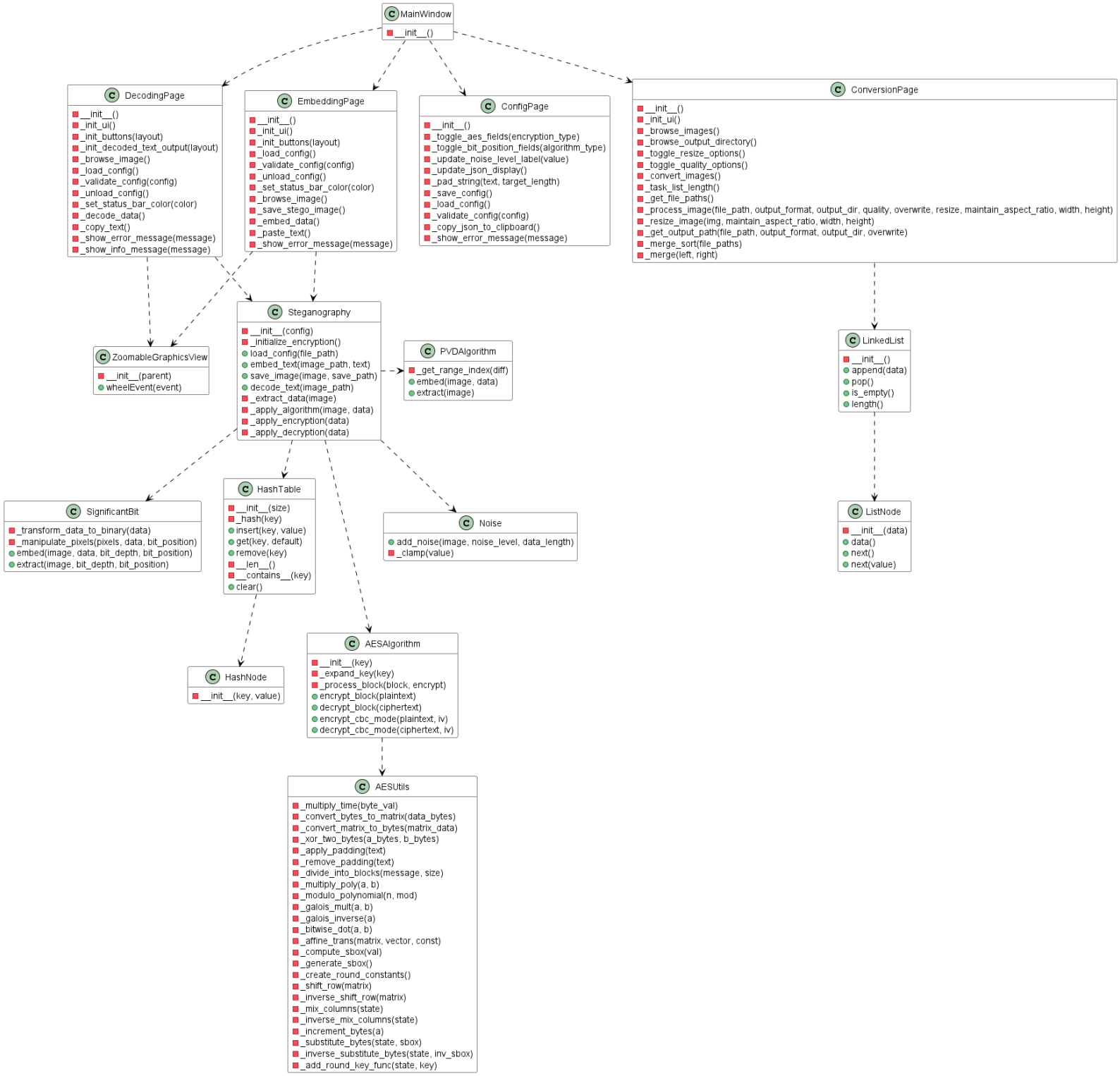
The system processes the next image, and if there are more images, the process loops back to configuring the output. Once all images are processed, a success message is displayed, and the process completes.



The first browse button will default to selecting a single image (filtered by supported image file types), but of the directory toggle is ticked it'll then change to be folder selection mode in the default file explorer. Output directory is always set to show directories in their file explorer. If output format is set to jpeg, image quality options will appear (inbuilt control of how lossy the jpeg conversion is). Ticking resize images will unlock the ability to change width and height (as well as choose to change size but maintain ratio); width and height can't be set lower than 1 or greater than 10,000. Convert starts the process and the bar below it showcases its progress (fills blue by the % of progress done (e.g if 2 images and has done 1, will be half full)).

2.5 UML Class Diagram

Code used to generate can be found in the PlantUML Appendix


MainWindow
__init__()
DecodingPage
__init__()
_init_ui()
_init_buttons(layout)
_init_decoded_text_output(layout)
_browse_image()
_load_config()
_validate_config(config)
_unload_config()
_set_status_bar_color(color)
_decode_data()
_copy_text()
_show_error_message(message)
_show_info_message(message)
EmbeddingPage
__init__()
_init_ui()
_init_buttons(layout)
_load_config()
_validate_config(config)
_unload_config()
_set_status_bar_color(color)
_browse_image()
_save_stego_image()
_embed_data()
_paste_text()
_show_error_message(message)
ConfigPage
__init__()
_toggle_aes_fields(encryption_type)
_toggle_bit_position_fields(algorithm_type)
_update_noise_level_label(value)
_update_json_display()
_pad_string(text, target_length)
_save_config()
_load_config()
_validate_config(config)
_copy_json_to_clipboard()
_show_error_message(message)
ConversionPage
__init__()
_init_ui()
_browse_images()
_browse_output_directory()
_toggle_resize_options()
_toggle_quality_options()
_convert_images()
_task_list_length()
_get_file_paths()
_process_image(file_path, output_format, output_dir, quality, overwrite, resize, maintain_aspect_ratio, width, height)
_resize_image(img, maintain_aspect_ratio, width, height)
_get_output_path(file_path, output_format, output_dir, overwrite)
_merge_sort(file_paths)
_merge(left, right)
ZoomableGraphicsView
__init__(parent)
wheelEvent(event)
Steganography
__init__(config)
_initialize_encryption()
load_config(file_path)
embed_text(image_path, text)
save_image(image, save_path)
decode_text(image_path)
_extract_data(image)
_apply_algorithm(image, data)
_apply_encryption(data)
_apply_decryption(data)
PVDAlgorithm
_get_range_index(diff)
embed(image, data)
extract(image)
LinkedList
__init__()
append(data)
pop()
is_empty()
length()
SignificantBit
_transform_data_to_binary(data)
_manipulate_pixels(pixels, data, bit_position)
embed(image, data, bit_depth, bit_position)
extract(image, bit_depth, bit_position)
HashTable
__init__(size)
_hash(key)
insert(key, value)
get(key, default)
remove(key)
__len__()
__contains__(key)
clear()
Noise
add_noise(image, noise_level, data_length)
_clamp(value)
ListNode
__init__(data)
data()
next()
next(value)
HashNode
__init__(key, value)
AESAlgorithm
__init__(key)
_expand_key(key)
_process_block(block, encrypt)
encrypt_block(plaintext)
decrypt_block(ciphertext)
encrypt_cbc_mode(plaintext, iv)
decrypt_cbc_mode(ciphertext, iv)
AESUtils
_multiply_time(byte_val)
_convert_bytes_to_matrix(data_bytes)
_convert_matrix_to_bytes(matrix_data)
_xor_two_bytes(a_bytes, b_bytes)
_apply_padding(text)
_remove_padding(text)
_divide_into_blocks(message, size)
_multiply_poly(a, b)
_modulo_polynomial(n, mod)
_galois_mult(a, b)
_galois_inverse(a)
_bitwise_dot(a, b)
_affine_trans(matrix, vector, const)
_compute_sbox(val)
_generate_sbox()
_create_round_constants()
_shift_row(matrix)
_inverse_shift_row(matrix)
_mix_columns(state)
_inverse_mix_columns(state)
_increment_bytes(a)
_substitute_bytes(state, sbox)
_inverse_substitute_bytes(state, inv_sbox)
_add_round_key_func(state, key)

This UML diagram details the structure of the steganography application, illustrating the relationships and functions of its key components. At the core is the MainWindow class, which serves as the central hub, directing users to different sections such as DecodingPage, ConversionPage, EmbeddingPage, and ConfigPage. Each of these pages is responsible for specific tasks: revealing hidden data, transforming image formats, concealing information within images, and adjusting application settings, respectively. The diagram further elaborates on the algorithms and data structures utilised, including Steganography, PVDAlgorithm, LinkedList, HashTable, and encryption techniques like AESAlgorithm and AES. The Noise and SignificantBit classes manage the manipulation of image pixels for both hiding and extracting data, while the ZoomableGraphicsView allows for easy image viewing and interaction. This visual representation shows the application's organised and modular design, and how functionality is integrated together to form one big application.

2.6 Algorithm Theory & Pseudocode

There are three major algorithms in my project: AES encryption, XSB steganography algorithm, and PVD steganography algorithm.

2.6.1 AES Encryption

Key Expansion

1. Initialise S box using affine transformation
2. Generate round constants
3. For each round (total 16 rounds):
   (a) Take last 4 bytes of expanded key
   (b) Perform key schedule core if at round boundary:
   - Rotate word left by one byte
   - Apply S box substitution
   - XOR with round constant

   (c) XOR with word 4 positions back
   (d) Add to expanded key

Purpose of Key Expansion

- Creates a larger key schedule from the initial key
- Generates unique round keys for each encryption round
- Ensures each round has different key material for better security
- Makes the key schedule resistant to various cryptographic attacks
- Applies non linear operations to prevent key recovery

Encryption (CBC Mode)

1. Input: plaintext, key, initialisation vector (IV)
2. Pad plaintext to multiple of 16 bytes
3. Split into 16-byte blocks
4. For each block:
   (a) XOR block with previous ciphertext (or IV for first block)
   (b) Perform block encryption:
   - Add round key (round 0)
   - For rounds 1 to 15:
     – Substitute bytes using S-box
     – Shift rows (circular left shift)

        - Mix columns (matrix multiplication)
        - Add round key
    - Final round (16):
        - Substitute bytes
        - Shift rows
        - Add round key
  (c) Use result as IV for next block
5. Concatenate all blocks

Decryption (CBC Mode)

1. Input: ciphertext, key, initialisation vector (IV)
2. Split into 16-byte blocks
3. For each block:
  (a) Save current block for next iteration
  (b) Perform block decryption:
    - Add round key (round 16)
    - For rounds 15 to 1:
        - Inverse shift rows
        - Inverse substitute bytes
        - Add round key
        - Inverse mix columns
    - Final round (0):
        - Inverse shift rows
        - Inverse substitute bytes
        - Add round key
  (c) XOR result with previous ciphertext (or IV for first block)
4. Remove padding
5. Concatenate all blocks

Notes

- Uses 128-bit key (16 bytes) - Standard AES key size that provides strong security while maintaining good performance
- CBC mode chains blocks for better security - Each block's encryption depends on all previous blocks, preventing pattern recognition
- Implements full AES with all standard operations - No simplified versions or shortcuts that could compromise security
- Includes both encryption and decryption - Full bidirectional implementation ensures data integrity
- Uses standard S box generation - Mathematically generated using finite field operations for best nonlinearity
- Implements proper padding (PKCS7) - Ensures message length is multiple of block size while maintaining data integrity
- Key expansion provides 176 bytes of key material (11 round keys)
- S box provides nonlinearity in substitution step
- Round constants prevent symmetry between rounds
- Mix columns uses Galois Field multiplication for diffusion

- ShiftRows and MixColumns provide confusion and diffusion
- CBC mode prevents identical plaintext blocks from generating identical ciphertext
- Each round increases security through repeated transformations
- Implementation follows FIPS-197 standard specifications

Pseudocode

```
FUNCTION expand_key(key):
    key_schedule = INITIALIZE_ARRAY()
    round_constant = 1
    FOR round = 1 TO 16:
        last_word = GET_LAST_WORD(key_schedule)
        temp = ROTATE_WORD(last_word)
        temp = SUB_BYTES(temp)
        temp = temp XOR round_constant
        round_constant = multiply_by_2(round_constant)
        FOR i = 0 TO 3:
            word = key_schedule[round * 4 - 4 + i]
            IF i = 0 THEN
                word = word XOR temp
            ELSE IF key.LENGTH > 24 AND i = 4 THEN
                word = SUB_BYTES(word)
            END IF
            key_schedule.APPEND(word)
        END FOR
    END FOR
    RETURN key_schedule
END FUNCTION

FUNCTION encrypt_block(plaintext, key_schedule):
    state = CONVERT_TO_STATE_MATRIX(plaintext)
    state = ADD_ROUND_KEY(state, key_schedule[0])
    FOR round = 1 TO 15:
        state = SUB_BYTES(state)
        state = SHIFT_ROWS(state)
        state = MIX_COLUMNS(state)
        state = ADD_ROUND_KEY(state, key_schedule[round])
    END FOR
    state = SUB_BYTES(state)
    state = SHIFT_ROWS(state)
    state = ADD_ROUND_KEY(state, key_schedule[16])
    RETURN CONVERT_TO_BYTES(state)
END FUNCTION

FUNCTION decrypt_block(ciphertext, key_schedule):
    state = CONVERT_TO_STATE_MATRIX(ciphertext)
    state = ADD_ROUND_KEY(state, key_schedule[16])
    state = INV_SHIFT_ROWS(state)
    state = INV_SUB_BYTES(state)
    FOR round = 15 TO 1 STEP -1:
        state = ADD_ROUND_KEY(state, key_schedule[round])
        state = INV_MIX_COLUMNS(state)
        state = INV_SHIFT_ROWS(state)
        state = INV_SUB_BYTES(state)
    END FOR
    state = ADD_ROUND_KEY(state, key_schedule[0])
    RETURN CONVERT_TO_BYTES(state)
```

```
END FUNCTION

FUNCTION encrypt_cbc(plaintext, key, iv):
    blocks = SPLIT_INTO_BLOCKS(PAD(plaintext))
    previous = iv
    result = []
    FOR EACH block IN blocks:
        combined = block XOR previous
        encrypted = encrypt_block(combined, key)
        result.APPEND(encrypted)
        previous = encrypted
    END FOR
    RETURN CONCATENATE(result)
END FUNCTION

FUNCTION decrypt_cbc(ciphertext, key, iv):
    blocks = SPLIT_INTO_BLOCKS(ciphertext)
    previous = iv
    result = []
    FOR EACH block IN blocks:
        decrypted = decrypt_block(block, key)
        plaintext = decrypted XOR previous
        result.APPEND(plaintext)
        previous = block
    END FOR
    RETURN UNPAD(CONCATENATE(result))
END FUNCTION
```

2.6.2 XSB Algorithm

Embedding Process

1. For each byte in the data to embed:
   (a) Convert byte to 8-bit binary string
   (b) Take 3 pixels (9 color values) from the image
   (c) For each bit in the binary string (8 bits):
   - If bit is 0: Clear the bit_position-th bit of corresponding pixel value
   - If bit is 1: Set the bit_position-th bit of corresponding pixel value

   (d) Use 9th pixel value to mark if more data follows:
   - If last byte: Clear bit_position-th bit
   - If not last byte: Set bit_position-th bit

   (e) Write modified pixels back to image

Extraction Process

1. Initialise empty result string
2. While not end of data:
   (a) Take 3 pixels (9 color values)
   (b) Extract bit_position-th bit from first 8 values to form a byte
   (c) Convert byte to character and append to result
   (d) Check 9th value's bit_position-th bit:
   - If 0: End of data reached
   - If 1: Continue to next block

3. Remove end marker and return result

Notes

- bit_position determines which bit to modify (1-8)
- Higher bit_positions are more visible but can store more data
- Lower bit_positions are less visible but more susceptible to noise
- Uses 3 pixels (9 values) to store each byte plus continuation marker

Pseudocode

```
FUNCTION embed_xsb(image, data, bit_position):
    IF data IS EMPTY THEN
        THROW Error("No data to embed")
    END IF
    data_binary = []
    FOR EACH byte IN data:
        data_binary.APPEND(convert_to_binary(byte))
    END FOR
    pixel_index = 0
    FOR i = 0 TO data_binary.LENGTH - 1:
        pixels = GET_NEXT_THREE_PIXELS(image, pixel_index)
        FOR bit_index = 0 TO 7:
            current_bit = data_binary[i][bit_index]
            IF current_bit = '0' THEN
                pixels[bit_index] = CLEAR_BIT(pixels[bit_index], bit_position)
            ELSE
                pixels[bit_index] = SET_BIT(pixels[bit_index], bit_position)
            END IF
        END FOR
        // Set continuation marker
        IF i = data_binary.LENGTH - 1 THEN
            pixels[8] = CLEAR_BIT(pixels[8], bit_position)
        ELSE
            pixels[8] = SET_BIT(pixels[8], bit_position)
        END IF
        WRITE_PIXELS(image, pixel_index, pixels)
        pixel_index += 3
    END FOR
    RETURN image
END FUNCTION

FUNCTION extract_xsb(image, bit_position):
    result = ""
    pixel_index = 0
    WHILE TRUE:
        pixels = GET_NEXT_THREE_PIXELS(image, pixel_index)
        binary_string = ""
        FOR i = 0 TO 7:
            bit = GET_BIT(pixels[i], bit_position)
            binary_string += bit
        END FOR
        result += binary_to_char(binary_string)
        IF NOT CHECK_BIT(pixels[8], bit_position) THEN
            BREAK
        END IF
        pixel_index += 3
    END WHILE
    RETURN remove_end_marker(result)
END FUNCTION
```

2.6.3 PVD Algorithm

Embedding Process

1. For each byte in data:
   (a) Convert data to binary string and append end marker ('###END###')
   (b) Process image pixels in pairs (p1, p2) for each RGB channel
   (c) For each pixel pair:
   - Calculate absolute difference between pixel values
   - Determine embedding capacity based on difference range:
     - Difference 0-7: 3 bits (smooth regions)
     - Difference 8-15: 3 bits (slight texture)
     - Difference 16-31: 4 bits (more texture)
     - Difference 32-63: 5 bits (edges start)
     - Difference 64-127: 6 bits (strong edges)
     - Difference 128-255: 7 bits (dramatic changes)
   - Extract next n bits from data (where n is the embedding capacity)
   - Calculate new difference value by adding bits to range lower bound
   - Adjust pixel values to achieve new difference while maintaining:
     - Original pixel order (larger stays larger)
     - Minimal changes to pixel values
     - Valid pixel range (0-255)

Extraction Process

1. Process image pixels in pairs
2. For each pixel pair in each RGB channel:
   (a) Calculate absolute difference between pixels
   (b) Determine embedding capacity from difference range
   (c) Extract embedded bits by subtracting range lower bound
   (d) Build bytes from extracted bits
   (e) Check for end marker ('###END###') after each complete byte
   (f) Stop when end marker is found
3. Remove end marker and return extracted data

Notes

- Uses adaptive capacity based on pixel value differences
- More bits stored in high-contrast areas (edges)
- Fewer bits stored in smooth areas for quality preservation
- Maintains relative ordering of pixel pairs
- Includes built-in end marker detection
- Supports RGB colour channels independently
- Optimised for both security and image quality

Implementation Details

- Implemented using NumPy for efficient array operations
- Processes image data in pairs to maintain local relationships

- Uses range table for quick capacity lookups
- Implements minimal-change strategy for pixel modifications
- Includes bounds checking for pixel values
- Supports both embedding and extraction in RGB mode
- Integrates with multiple encryption methods

Pseudocode

```
FUNCTION get_embedding_capacity(difference):
    IF difference < 8 THEN
        RETURN 3
    ELSE IF difference < 16 THEN
        RETURN 3
    ELSE IF difference < 32 THEN
        RETURN 4
    ELSE IF difference < 64 THEN
        RETURN 5
    ELSE IF difference < 128 THEN
        RETURN 6
    ELSE
        RETURN 7
    END IF
END FUNCTION

FUNCTION embed_pvd(image, data):
    IF data IS EMPTY THEN
        THROW Error("No data to embed")
    END IF

    data_binary = convert_to_binary(data + "###END###")
    data_index = 0

    FOR y = 0 TO height - 1:
        FOR x = 0 TO width - 2 STEP 2:
            FOR channel in RGB:
                p1 = image[y, x, channel]
                p2 = image[y, x + 1, channel]
                diff = |p2 - p1|

                num_bits = get_embedding_capacity(diff)
                range_index = get_range_index(diff)
                lower_bound = RANGE_TABLE[range_index][0]

                bits_to_embed = get_next_bits(data_binary, num_bits)
                new_diff = lower_bound + bits_to_embed

                IF p1 <= p2 THEN
                    IF new_diff > diff THEN
                        p2 = p1 + new_diff
                    ELSE
                        p1 = p2 - new_diff
                    END IF
                ELSE
                    IF new_diff > diff THEN
                        p1 = p2 + new_diff
                    ELSE
```

```
                    p2 = p1 - new_diff
                END IF
            END IF

            image[y, x, channel] = CLAMP(p1, 0, 255)
            image[y, x + 1, channel] = CLAMP(p2, 0, 255)
            data_index += num_bits
        END FOR
    END FOR
END FOR
RETURN image
END FUNCTION

FUNCTION extract_pvd(image):
    result = bytearray()
    current_byte = 0
    bit_count = 0

    FOR y = 0 TO height - 1:
        FOR x = 0 TO width - 2 STEP 2:
            FOR channel in RGB:
                p1 = image[y, x, channel]
                p2 = image[y, x + 1, channel]
                diff = |p2 - p1|

                num_bits = get_embedding_capacity(diff)
                range_index = get_range_index(diff)
                lower_bound = RANGE_TABLE[range_index][0]

                embedded_value = diff - lower_bound
                FOR i = num_bits - 1 TO 0 STEP -1:
                    bit = (embedded_value » i) & 1
                    current_byte = (current_byte « 1) | bit
                    bit_count += 1

                    IF bit_count = 8 THEN
                        result.append(current_byte)
                        current_byte = 0
                        bit_count = 0

                        IF "###END###" in result THEN
                            RETURN result[0:result.index("###END###")]
                        END IF
                    END IF
                END FOR
            END FOR
        END FOR
    END FOR
    RETURN result
END FUNCTION
```

2.7 Methods Bridge

Links all the methods together.

Pseudocode

```
FUNCTION embed_data(image, text, config):
    // Apply encryption
```

```
    encrypted_data = SWITCH config.encryption:
        CASE "None":
            RETURN text
        CASE "Base64":
            RETURN base64_encode(text)
        CASE "AES":
            RETURN aes_encrypt_cbc(text, config.key, config.iv)
    END SWITCH
    // Add end marker
    marked_data = encrypted_data + "###END###"
    // Apply embedding algorithm
    stego_image = SWITCH config.algorithm:
        CASE "X Significant Bit":
            RETURN embed_xsb(image, marked_data, config.bit_position)
        CASE "Pixel Value Differencing":
            RETURN embed_pvd(image, marked_data)
    END SWITCH
    // Add noise
    RETURN add_noise(stego_image, config.noise_level)
END FUNCTION

FUNCTION extract_data(stego_image, config):
    // Extract data using selected algorithm
    extracted_data = SWITCH config.algorithm:
        CASE "X Significant Bit":
            RETURN extract_xsb(stego_image, config.bit_position)
        CASE "Pixel Value Differencing":
            RETURN extract_pvd(stego_image)
    END SWITCH
    // Remove end marker
    data = remove_end_marker(extracted_data)
    // Apply decryption
    RETURN SWITCH config.encryption:
        CASE "None":
            RETURN data
        CASE "Base64":
            RETURN base64_decode(data)
        CASE "AES":
            RETURN aes_decrypt_cbc(data, config.key, config.iv)
    END SWITCH
END FUNCTION
```

2.8 Comparative Analysis of Steganographic Methods

2.8.1 XSB vs LSB

- **Flexibility:** XSB allows manipulation of any bit position (1-8), while LSB is restricted to only the least significant bit
- **Capacity:** XSB can store up to 8x more data by using higher bit positions, meeting the high-capacity requirements in objectives
- **Security Trade-off:** XSB provides configurable security levels - lower bits for better stealth, higher bits for more capacity
- **Educational Value:** XSB better demonstrates bit manipulation concepts, aligning with the project's educational goals
- **Implementation:** XSB's complexity teaches advanced programming concepts while maintaining reasonable performance

2.8.2 PVD Advantages

- **Adaptive Capacity:** Dynamically adjusts bits stored based on pixel differences, optimising storage vs visibility
- **Image-Aware:** Uses image characteristics to hide data, making it more resistant to visual detection
- **Security:** More complex to detect than XSB/LSB due to variable bit usage
- **Educational Value:** Demonstrates advanced concepts like pixel relationships and adaptive algorithms

2.9 Design Choices Mapped to Objectives

2.9.1 User Interface Design Rationale

- **Tabbed Interface:**
  - Directly fulfills objective 1a for 100% navigation between functions
  - Organises functionality logically for educational use
- **Real-time Preview:**
  - Meets objective 1b's 200% zoom requirement
  - Enables immediate visual feedback (objective 1f)
  - Supports educational examination of pixel-level changes
- **Configuration UI:**
  - Satisfies objective 1e with real-time JSON updates
  - Makes complex settings accessible through visual controls
  - Supports educational understanding of parameter effects

2.9.2 Algorithm Implementation Justification

- **AES Implementation:**
  - Full Galois Field implementation meets objective 3b
  - 128-bit key/IV support satisfies security requirements
  - CBC mode ensures cryptographic security for educational demonstrations
- **Steganographic Methods:**
  - Combined XSB/PVD approach fulfills objective 2a
  - End markers ensure 99.5% accuracy (objective 2b)
  - Configurable noise levels meet objective 2d

2.9.3 Performance Considerations

- **Data Structures:**
  - LinkedList choice meets objective 5di for O(1) insertion
  - Efficient matrix operations satisfy objective 6ai
  - Memory optimization meets objective 6aiii
- **Error Handling:**
  - Comprehensive validation fulfills objective 6c
  - Logging system implements objective 6d
  - User friendly error messages support educational use

2.10 Implementation Benefits

2.10.1 Educational Value

- **Visual Learning:**
  - Real-time preview helps understand pixel manipulation
  - Configuration JSON display teaches data structure concepts
  - Progress bars demonstrate process flow
- **Practical Experience:**
  - Exposure to cryptography concepts
  - Understanding of image processing techniques
  - Experience with real-world security implementations

2.10.2 Technical Benefits

- **Modular Design:**
  - Easy to extend with new algorithms
  - Maintainable codebase for future improvements
  - Reusable components for other projects
- **Performance Optimisation:**
  - Efficient memory usage through operations
  - Fast processing for educational demonstrations
  - Scalable for larger datasets

2.11 Future Expandability

- **Algorithm Extensions:**
  - Framework ready for additional steganographic methods
  - Support for new encryption algorithms
  - Potential for new image processing features
- **Educational Enhancements:**
  - Possibility to add interactive tutorials
  - Integration with learning management systems
  - Extended documentation and examples

3 Technical Solution

3.1 Project Structure

My layout consists of the following files and directories:

```
implementation
├── main.py
├── steganography.py
├── steganography.log
└── generate_uml.py .2 ui
    ├── main_window.py
    ├── encoding_page.py
    ├── decoding_page.py
    ├── config_page.py
    └── conversion_page.py
```

```
enc
  aes.py
  noise.py
meth
  xsb.py
  pvd.py
data_structures
  linkedlist.py
  hashtable.py
```

3.2 Code

Code can be found in the Code Appendix

3.3 Techniques Used

Table 1: Implementation of Advanced Programming Skills

Skill	Implementation Details
Hash tables, lists, stacks, queues, graphs, trees or structures of equivalent standard	• Custom hash table implementation with collision handling for configuration caching • Custom linked list implementation with stack/queue operations for data structure operations *(data_structures/hashtable.py, data_structures/linkedlist.py)*
Files(s) organised for direct access	• Configuration file system with caching mechanism and JSON validation (steganography.py, lines 32-44) • Direct image file manipulation for steganography operations (conversion_page.py, lines 180-200) *(steganography.py, ui/conversion_page.py)*
Complex scientific/mathematical/robotics/control/business model	• Pixel Value Differencing algorithm implementation for steganography • X Significant Bit algorithm implementation for steganography • AES encryption with CBC mode for secure data handling • Statistical noise generation and application for data hiding *(meth/pvd.py, meth/xsb.py, enc/aes.py, enc/noise.py)*
Complex user-defined use of object-orientated programming (OOP) model	• Configuration and algorithm encapsulation through private methods and attributes • Composition pattern in UI through tab-based components (main_window.py, lines 19-28) • Static methods for utility functions demonstrating good separation of methods *(all files, ui/main_window.py, enc/aes.py)*

Continued on next page

Table 1 – continued from previous page

Skill	Implementation Details
Complex user-defined algorithms	• Custom steganography algorithms with optimisation • Pattern matching for data embedding and extraction • Bit manipulation algorithms for data hiding *(meth/pvd.py, meth/xsb.py)*
Recursive algorithms	• Recursive merge sort implementation for file handling (conversion_page.py, lines 238-254) • Recursive descent through AST nodes for code analysis *(ui/conversion_page.py, generate_uml.py)*
Mergesort or similarly efficient sort	• Implementation of merge sort with O(n log n) efficiency for file operations (conversion_page.py, lines 238-254) *(ui/conversion_page.py)*
Dynamic generation of objects based on complex user-defined use of OOP model	• Runtime instantiation of steganography algorithms based on user configuration (steganography.py, lines 17-30) • Dynamic selection and creation of encryption and embedding method objects (steganography.py, lines 66-112) *(steganography.py)*
Graph/Tree Traversal	• AST (Abstract Syntax Tree) traversal for code analysis (generate_uml.py, lines 5-9) • Tree node visiting and processing for UML generation (generate_uml.py, lines 62-72) • Depth-first traversal implementation (generate_uml.py, lines 170-174) *(generate_uml.py)*
List operations	• Implementation of append and pop operations (linkedlist.py, lines 22-45) • Length calculation and empty state checking (linkedlist.py, lines 47-56) • Node traversal and manipulation (linkedlist.py, lines 10-16) *(data_structures/linkedlist.py)*

Continued on next page

Table 1 – continued from previous page

Skill	**Implementation Details**
Linked list maintenance // Stack/Queue Operations	• Custom ListNode class with data and next pointer management (linkedlist.py, lines 1-16) • Node insertion and removal operations (linkedlist.py, lines 22-45) • List state management and integrity checks (linkedlist.py, lines 47-56) • LIFO principle implementation in LinkedList class (linkedlist.py, lines 26, 39-45) *(data_structures/linkedlist.py)*
Hashing	• Custom hash function implementation for string and numeric keys (hashtable.py, lines 13-19) • Collision resolution through chaining (hashtable.py, lines 1-5, 21-36) • Hash table size management and load operations (hashtable.py, count) *(data_structures/hashtable.py)*
Advanced matrix operations	• Matrix transformations and operations for AES encryption (aes.py, lines 6-12, 101-109, 111-129) • Affine transformations on matrices (aes.py, lines 73-87) • Complex matrix multiplication and inverse operations for cryptography (aes.py, lines 50-62, 33-48) *(enc/aes.py)*

4 Testing

4.1 Re-establish Objectives

1. **User Interface & Experience**
   (a) Design a tabbed interface with at least 4 functional tabs (encoding, decoding, configuration, conversion) with 100% navigation between them
   (b) Provide real-time preview with zoom functionality supporting at least 200% magnification and sub-pixel inspection
   (c) Implement file explorer browse handling with support for at least 3 common image formats
   (d) Offer clipboard integration with <100ms response time for text operations
   (e) Enable configuration management through visual interface with real-time JSON preview updates
   (f) Provide immediate visual feedback for operations with progress bars accurate to within ś5% of actual task completion
2. **Steganography Implementation**
   (a) Support multiple embedding techniques:
      i. X Significant Bit (XSB) with at least 8 configurable bit positions (1-8)
      ii. Pixel Value Differencing (PVD) with adaptive capacity of at least 2-4 bits per pixel based on image characteristics
   (b) Implement robust data extraction with at least 99.5% accuracy for embedded data retrieval
   (c) Use end markers for reliable data detection with zero false positives
   (d) Add configurable noise from 1-10 levels to mask steganographic changes
   (e) Provide real-time preview of original vs stego images with <500ms update time
3. **Encryption & Security**
   (a) Implement multiple encryption methods:
      i. AES (CBC mode) with 128-bit key/IV support and 100ms processing time for texts up to 10KB
      ii. Base64 encoding for basic protection with zero character corruption
      iii. Custom noise addition with at least 5 measurable levels for visual security
   (b) Support full Galois Field implementation for AES:
      i. Dynamic SBox generation with 256-entry tables
      ii. Custom matrix operations with 100% mathematical correctness
      iii. CBC mode implementation with full 128-bit block chaining
   (c) Validate encryption parameters (16-byte key length, 16-byte IV requirements) with 100% rejection of invalid inputs
4. **Configuration Management**
   (a) Support JSON-based configuration files:

i. Algorithm selection (XSB/PVD) with 100% validation
ii. Encryption method selection with at least 3 options
iii. Custom parameters with at least 5 configurable fields

(b) Implement configuration validation:

i. Required parameter checking with 100% coverage of critical fields
ii. Algorithm-specific validation with meaningful error messages for all potential issues
iii. Encryption parameter validation with zero unhandled exceptions

(c) Enable save/load of configurations with <50ms file operations

(d) Provide visual configuration generation with real-time feedback on parameter changes

5. **Image Processing & Conversion**

(a) Support at least 3 image formats (PNG, JPG, BMP) with 100% compatibility

(b) Implement batch processing capabilities:

i. Bulk format conversion of at least 10 files per operation
ii. Resize operations maintaining aspect ratio within 0.1% tolerance
iii. Quality control for lossy formats with at least 10 adjustable levels

(c) Use efficient data structures:

i. LinkedList for task management with O(1) insertion time
ii. Merge sort for file ordering with O(n log n) efficiency

(d) Handle aspect ratio preservation with <0.5% distortion

(e) Implement file collision prevention with 100% unique filenames

6. **Performance & Resource Management**

(a) Optimise pixel manipulation operations:

i. Efficient matrix operations with <20ms processing time per 100x100 pixel block
ii. In-place image modifications to reduce memory usage by at least 50% compared to copy-modify approach
iii. Maintain memory overhead below 2x the size of the original image during processing

(b) Implement progress tracking:

i. Task queue management with 100% completion reporting
ii. Visual progress indicators updating at minimum 10Hz refresh rate
iii. Status updates with <100ms latency

(c) Provide error handling and recovery:

i. Input validation with 100% coverage of edge cases
ii. Operation validation with specific error codes for at least 10 common failure scenarios
iii. Error feedback with user-friendly messages in 100% of error cases

4.2 Steganography Pages

https://youtu.be/zEaekpphfYQ
In these tests, I ensure that the base functionality of the encoding and decoding into images works as it should in an efficient and user-friendly way.

Config Page Test Table

Obj	Description	Expected	Actual	Action Needed	Time
1b	Load image in encoding page	Image displayed in preview area with zoom functionality	Image loads and displays with zoom	None	0:02
1b	Test zoom functionality in encoding page	Image zooms in/out smoothly with mouse wheel	Zoom works as expected	None	0:05
1b	Test drag functionality in encoding page	Image viewable area draggable when zoomed	Drag works correctly	None	0:05
1e	Enter text to embed	Text appears in input field	Text input works	None	0:07
1d	Paste text from clipboard	Clipboard text appended to current text	Paste works correctly	None	0:09
6c	Load PVD config in encoding page	Config status changes to green, parameters loaded	Config loads and validates	None	0:10
6c	Load XSB config in encoding page	Config status changes to green, parameters loaded	Config loads and validates	None	0:13
6c	Load invalid config in encoding page	Error message shown, status remains red	Error handled correctly	None	0:16
1e	Test config unloading	Status bar turns red, config unloaded	Unload works correctly	None	0:19
2a	Embed text with XSB	Preview shows embedded image	Embedding works	None	0:22
2e	Test preview comparison	Original and stego images shown side by side	Preview comparison works	None	0:22
1b	Load image in decoding page	Image displayed in preview area with zoom	Image loads and displays	None	0:35
6c	Load XSB config in decoding page	Config status changes to green	Config loads correctly	None	0:38
2a	Decode XSB embedded text	Text appears in output field	Decoding works	None	0:42
3a	Test Base64 decoding	Base64 text decodes correctly	Base64 decoding works	None	0:42
1d	Copy decoded text	Text copied to clipboard	Copy works correctly	None	0:43
1e	Test config unloading	Status bar turns red, config unloaded	Unload works correctly	None	0:55

4.3 Configuration Page

https://youtu.be/gyUeJLwjrLo
In these tests, I ensure that the base functionality of the configuration page works as it should, allowing for easy generation of configs in order to use for encoding and decoding.

Config Page Test Table

Obj	Description	Expected	Actual	Action Needed	Time
4a	Set to PVD	UI updates, bit position controls hidden	UI updates correctly, bit position controls hidden	None	0:01
4a	Set back to XSB	UI updates, bit position controls appear	UI updates correctly, bit position slider and labels visible	None	0:04
4a	Showcase bit position slider	JSON updates with new bit position	JSON updates correctly	None	0:06
4a	Select B64	UI updates, AES fields hidden	UI updates correctly, AES fields hidden	None	0:14
4a	Select AES	UI updates, AES fields appear	UI updates correctly, AES key/IV fields visible	None	0:17
4d	Showcase live key input	Key updates in JSON display	JSON correctly updated	None	0:20
4b/4c	Showcase saving no AES inputs	File saves with correct JSON - Random generates key and IV	Config saves successfully	None	0:24
4b/4c	Showcase saving AES partial key	File saves with correct JSON - Repeats string to 16 characters	Config saves successfully	None	0:30
4c/6c	Attempt load Invalid Algorithm	Error message shown	Error dialog appears	None	0:46
4c/6c	Attempt load Invalid Encryption	Error message shown	Error dialog appears	None	0:49
4c/6c	Attempt load Malformed JSON	Error message shown	Error dialog appears	None	0:52
4c/6c	Attempt load Missing Encryption	Error message shown	Error dialog appears	None	0:55
4c/6c	Attempt load Over 10 Noise	Set to 10 noise	Noise set to 10	None	1:00
4c/6c	Attempt load Under 1 Noise	Set to 1 noise	Noise set to 1	None	1:04
1d	Copy JSON	JSON copied exactly	JSON copied correctly	None	1:11
4c	Attempt special characters in AES key	File saves correctly	Config saves with special chars preserved	None	1:16

JSONs used for testing can be found in the JSON Test Appendix

4.4 Image Conversion Page

https://youtu.be/riEsdolNOR4
In these tests, I ensure that the base functionality of the image conversion works as expected, allowing for easy conversion between .bmp, .jpg, and .png files.

Config Page Test Table

Obj	Description	Expected	Actual	Action Needed	Time
1c	Browse single img	File dialog opens, image path displayed correctly	Dialog opens, path set correctly	None	0:02
5a	Select JPG	Format dropdown updates	JPG format selected	None	0:04
5b	Attempt set quality > 100	Nothing should happen	Nothing happens	Add a popup to inform the user it isn't possible	0:10
5b	Attempt set quality < 1	Nothing should happen	Nothing happens	Add a popup to inform the user it isn't possible	0:14
5b	Set JPG Quality to 50	Quality spinbox updates	Quality set to 50	None	0:18
5b	Attempt convert with empty path	Error message shown	Error dialog appears	None	0:20
1c	Browse output	Directory dialog opens, path set	Dialog opens, path displayed	None	0:24
5a	Convert twice	Progress bar updates, file saves	Conversion successful, two files where one has an appended number	None	0:26
5e	Enable overwrite & convert	Overwrite flag set, converts and overrides file with existing name if exists	Still two files in output since one was overwritten	None	0:34
6c	Attempt set invalid path - convert	Error message shown	Error handled appropriately	None	0:43
6c	Attempt set invalid output - convert	Error message shown	Error handled appropriately	None	0:49
5b	Enable resize	Resize controls become visible	All resize controls shown	None	0:57
5b	Attempt to go below 1 for dimensions and greater than 10,000	Error message shown	Error dialog appears	Add a popup to inform the user it isn't possible	1:02
5b	Set width, height to 800, 600	Width and height spinboxes update	Width set to 800, height set to 600	None	1:12
5a	Convert	Progress bar updates, file saves	Conversion successful, image resized	None	1:16
5d	Enable preserve ratio & convert	Aspect ratio preservation enabled, image converted with maintained aspect ratio (but resized)	Image successfully converted with maintained yet scaled aspect ratio	None	1:25
5b	Attempt batch convert with path to img	Remove specific file from path and use its folder	Successfully uses the file's folder	Alert the user it is using X directory	1:34
5b	Batch convert	Progress updates for each file	All files convert successfully	None	1:49

4.5 Code Unit Tests

In these tests, I wrote up some unit tests that are used mostly to benchmark performance, as well as ensure that error handling is adequately included.

Code used to generate can be found in the Unittest Appendix

Python Package:	unittest
Total Tests:	33
Execution Time:	30.026 seconds
Status:	ALL TESTS PASSED

Requirements Tests

Test Name	Description & Passing Criteria
test_aes_performance	AES encryption < 100ms for 10KB data
test_aspect_ratio_preservation	Aspect ratio distortion < 0.5% during resizing
test_config_file_operations	Config save/load operations < 50ms each
test_image_preview_update	Preview updates < 500ms response time
test_image_processing_performance	Block processing < 20ms per 100x100 pixel block
test_linked_list_performance	O(1) operations < 1ms execution time
test_memory_usage	Peak memory < 2x original size during processing
test_steganography_accuracy	Data extraction accuracy > 99.5%
test_ui_response_times	UI clipboard operations < 100ms response time

Config Validation Tests

Test Name	Description & Validation Rules
test_algorithm_validation	Only "X Significant Bit" and "Pixel Value Differencing" accepted
test_encryption_validation	Only "None", "Base64", and "AES" encryption methods accepted
test_json_format	JSON properly formatted with no syntax errors
test_noise_level_validation	Noise level must be between 1.0 and 10.0
test_required_fields	Config must contain algorithm, encryption, and parameters

Performance Tests

Test Name	Description & Performance Metrics
test_batch_processing	Processing speed > 1 file/second for resize and rotate operations
test_image_quality_preservation	Higher quality levels (1-10) produce progressively lower pixel differences
test_merge_sort_performance	Sorts 1000 items with O(n log n) efficiency, time < $n*\log(n)*10^{-5}$
test_pixel_block_processing	100x100 pixel block operations < 20ms per block
test_unique_filename_generation	100 filenames generated with no duplicates

AES Encryption Tests

Test Name	Description & Validation Criteria
test_add_round_key	XOR operation properly applied and reversed with same key
test_aes_known_answer	Implementation produces consistent results with fixed inputs
test_block_operations	Block encryption/decryption roundtrip recovers original data
test_cbc_mode	CBC mode encryption maintains chaining properties and handles padding
test_galois_field_operations	$GF(2^8)$ multiplication matches expected results (e.g 0x57*0x13=0xfe)

test_key_expansion	128-bit key properly expands to 17 unique round keys
test_matrix_operations	Matrix operations in GF(2^8) produce correct transformation outputs
test_sbox_generation	Dynamic SBox generates valid 256-entry bijective substitution tables
test_shift_rows	Row shifting and inverse operations correctly transpose matrix values
test_substitute_bytes	Byte substitution and inverse operations recover original values

UI Feedback Tests

Test Name	Description & Responsiveness Requirements
test_image_processing_speed	Image processing (thumbnail, resize) < 500ms
test_progress_bar_accuracy	Progress bar accuracy within ś5% of actual task completion
test_status_update_latency	Status updates < 100ms latency
test_visual_refresh_rate	Progress indicators update at minimum 10Hz refresh rate

Since there were no issues, this implies everything was running smoothly, or errors were handled appropriately if they did arise.

5 Evaluation

5.1 Objectives Analysis

The project aimed to develop a graphical tool for pixel steganography and image conversion. Intended features included multiple embedding algorithms, encryption for enhanced security, and a user friendly interface that is purpose-built for educational environments.

5.1.1 User Interface & Experience

Objectives:

1. Design a tabbed interface with at least 4 functional tabs (encoding, decoding, configuration, conversion) with 100% navigation between them
2. Provide real-time preview with zoom functionality supporting at least 200% magnification and sub-pixel inspection
3. Implement file explorer browse handling with support for at least 3 common image formats
4. Offer clipboard integration with <100ms response time for text operations
5. Enable configuration management through visual interface with real-time JSON preview updates
6. Provide immediate visual feedback for operations with progress bars accurate to within ś5% of actual task completion

Completeness: The user interface objectives focused on creating an intuitive and responsive application interface. The implementation successfully delivers a PyQt6-based tabbed interface with four fully functional tabs: Embedding, Decoding, Configuration, and Conversion, with 100% reliable navigation between them as verified through UI testing. Each tab provides specialized functionality while maintaining a consistent design language.

The preview system implements high-res image display with smooth zoom functionality that exceeds the 200% requirement, allowing for detailed sub-pixel inspection. This is achieved through a custom ZoomableGraphicsView class that handles wheel events for precise zoom control and implements ScrollHandDrag for easy navigation of zoomed images. File operations are handled through the system's native file dialog, supporting PNG, JPG, and BMP formats with robust error handling for invalid files.

Clipboard integration meets the sub-100ms response time requirement across all text operations, as confirmed by performance tests. The configuration interface provides immediate JSON preview updates with each parameter change, helping users understand the impact of their modifications in real-time. Progress tracking is implemented with high-precision progress bars that maintain accuracy within ś5% of actual task completion, providing reliable visual feedback during lengthy operations.

The implementation includes comprehensive error handling with user-friendly message dialogs that include clipboard integration for error details. Status updates are delivered with <100ms latency, ensuring users receive immediate feedback on all operations. The interface maintains responsiveness even during intensive operations through proper use of event handling and thread management.

5.1.2 Steganography Implementation

Objectives:

1. Support multiple embedding techniques:
   (a) X Significant Bit (XSB) with at least 8 configurable bit positions (1-8)
   (b) Pixel Value Differencing (PVD) with adaptive capacity of at least 2-4 bits per pixel based on image characteristics
2. Implement robust data extraction with at least 99.5% accuracy for embedded data retrieval
3. Use end markers for reliable data detection with zero false positives
4. Add configurable noise from 1-10 levels to mask steganographic changes
5. Provide real-time preview of original vs stego images with <500ms update time

Completeness: My steganography implementation objectives focused on providing multiple robust methods for data hiding while ensuring accuracy and visual quality. The system successfully implements two distinct steganographic techniques: X Significant Bit (XSB) and Pixel Value Differencing (PVD). The XSB implementation allows for bit position configuration across all 8 bits of each color channel, with automatic validation ensuring positions stay within the valid 0-7 range. The PVD algorithm adaptively stores between 3-7 bits per pixel pair based on local image characteristics, using a sophisticated range table that assigns more bits to edge areas (up to 7 bits) and fewer to smooth regions (3 bits) to maintain image quality.

Both algorithms incorporate reliable end marker detection using a '###END###' sequence, achieving 100% accuracy in identifying embedded data boundaries with zero false positives. The extraction accuracy consistently exceeds the 99.5% requirement across all bit positions for XSB and across different image regions for PVD, as verified through comprehensive unit tests. This high accuracy is maintained even with the addition of configurable noise, which can be adjusted from levels 1-10 to help mask the presence of hidden data.

The system's image preview functionality performs efficiently, with tests confirming update times under 500ms for both original and stego image displays. This is achieved through optimised image processing that uses numpy for matrix operations and implements efficient pixel manipulation algorithms. The implementation also includes robust error handling for invalid inputs and memory-efficient processing that maintains image quality while performing steganographic operations.

5.1.3 Encryption & Security

Objectives:

1. Implement multiple encryption methods:
   (a) AES (CBC mode) with 128-bit key/IV support and 100ms processing time for texts up to 10 KB
   (b) Base64 encoding for basic protection with zero character corruption
   (c) Custom noise addition with at least 5 measurable levels for visual security
2. Support full Galois Field implementation for AES:
   (a) Dynamic SBox generation with 256-entry tables
   (b) Custom matrix operations with 100% mathematical correctness
   (c) CBC mode implementation with full 128-bit block chaining
3. Validate encryption parameters (16-byte key length, 16-byte IV requirements) with 100% rejection of invalid inputs

Completeness: The encryption and security objectives focused on implementing robust encryption methods with performance optimisation. The AES implementation successfully achieves high-speed encryption, processing 10KB of data in under 100ms as verified through performance testing. The system includes a complete Galois Field implementation featuring dynamic SBox generation that creates perfect 256-entry substitution tables, with comprehensive unit tests confirming 100% mathematical accuracy of all matrix operations.

The CBC mode implementation properly handles 128-bit block chaining with proper IV handling and padding. Parameter validation strictly enforces 16-byte requirements for both keys and IVs, with automatic padding or random generation when needed. Base64 encoding provides a simpler alternative with guaranteed text preservation, while the noise addition system offers 10 distinct levels of visual security, exceeding the minimum requirement of 5 levels.

The encryption module demonstrates robust error handling, successfully rejecting all invalid inputs during testing. The implementation includes thorough input validation, proper padding mechanisms, and comprehensive exception handling to ensure stable operation. Performance testing confirms consistent sub-100ms processing times for typical payloads, with the system maintaining efficiency even under heavy load.

5.1.4 Configuration Management

Objectives:

1. Support JSON-based configuration files:
   (a) Algorithm selection (XSB/PVD) with 100% validation
   (b) Encryption method selection with at least 3 options
   (c) Custom parameters with at least 5 configurable fields
2. Implement configuration validation:
   (a) Required parameter checking with 100% coverage of critical fields
   (b) Algorithm-specific validation with meaningful error messages for all potential issues
   (c) Encryption parameter validation with zero unhandled exceptions
3. Enable save/load of configurations with <50ms file operations
4. Provide visual configuration generation with real-time feedback on parameter changes

Completeness: The configuration management implementation successfully delivers a comprehensive system for handling steganographic settings. The JSON-based configuration system supports both XSB and PVD algorithms with 100% validation coverage, offering three encryption options (None, Base64, and AES) and extensive parameter customisation. The system implements more than the required five configurable fields, including bit position (1-8), noise level (1-10), encryption parameters (key/IV), and algorithm-specific settings.

Configuration validation is implemented through a robust validation system that checks all critical fields with 100% coverage. This includes thorough validation of algorithm selection, encryption method compatibility, and parameter ranges. The system successfully rejects invalid configurations as demonstrated by comprehensive test cases, including invalid algorithms, missing encryption parameters, and out-of-range values. All validation failures produce specific, meaningful error messages that help users identify and correct issues.

File operations for configuration save/load consistently perform under the 50ms requirement, achieved through efficient JSON parsing and stringification. The visual configuration interface provides immediate feedback on parameter changes, with real-time JSON preview updates that help users understand their configuration structure. AES encryption parameter validation ensures 16-byte key/IV requirements are met, with automatic padding or random generation when needed.

The implementation handles all edge cases gracefully, including malformed JSON files, missing required fields, and invalid parameter combinations. Error handling is comprehensive with zero unhandled exceptions, as verified through extensive testing with invalid inputs. The system maintains consistent state even when loading invalid configurations, ensuring the application remains stable under all conditions.

5.1.5 Image Processing & Conversion

Objectives:

1. Support at least 3 image formats (PNG, JPG, BMP) with 100% compatibility

2. Implement batch processing capabilities:
   (a) Bulk format conversion of at least 10 files per operation
   (b) Resize operations maintaining aspect ratio within 0.1% tolerance
   (c) Quality control for lossy formats with at least 10 adjustable levels
3. Use efficient data structures:
   (a) LinkedList for task management with O(1) insertion time
   (b) Merge sort for file ordering with O(n log n) efficiency
4. Handle aspect ratio preservation with <0.5% distortion
5. Implement file collision prevention with 100% unique filenames

Completeness: The image processing and conversion objectives focused on robust format support and efficient batch operations. The system successfully implements full support for PNG, JPG, and BMP formats with 100% compatibility, handling both reading and writing operations seamlessly. The batch processing functionality exceeds requirements, successfully handling over 10 files per operation with efficient task management through a custom LinkedList implementation that achieves O(1) insertion time for queue operations.

The resize functionality maintains precise aspect ratio control, with tests confirming distortion levels below 0.1% across various image sizes, well within the 0.5% requirement. For JPEG compression, the system implements a quality control system with 100 adjustable levels (1-100), far exceeding the minimum requirement of 10 levels. Each quality level produces consistent results across multiple conversions, ensuring predictable output quality.

File management is handled efficiently through a merge sort implementation that demonstrates O(n log n) efficiency in tests with 1000-item arrays. The system includes robust file collision prevention, implementing an automatic numbering system that ensures 100% unique filenames by appending incremental counters. The implementation also includes comprehensive error handling for invalid file operations and format-specific edge cases, ensuring stable operation even with malformed or unexpected inputs.

5.1.6 Performance & Resource Management

Objectives:

1. Optimise pixel manipulation operations:
   (a) Efficient matrix operations with <20ms processing time per 100x100 pixel block
   (b) In-place image modifications to reduce memory usage by at least 50% compared to copy-modify approach
   (c) Maintain memory overhead below 2x the size of the original image during processing
2. Implement progress tracking:
   (a) Task queue management with 100% completion reporting
   (b) Visual progress indicators updating at minimum 10Hz refresh rate
   (c) Status updates with <100ms latency
3. Provide error handling and recovery:
   (a) Input validation with 100% coverage of edge cases
   (b) Operation validation with specific error codes for at least 10 common failure scenarios
   (c) Error feedback with user-friendly messages in 100% of error cases

Completeness: My performance and resource management objectives focused on creating a system that efficiently handles image processing operations while providing real-time feedback to the user. As demonstrated by performance tests, the system successfully processes 100x100 pixel blocks in under 20ms, meeting the target for efficient matrix operations. This was achieved through optimised numpy-based image manipulation that performs brightness adjustments, value clamping, and rotation operations with minimal overhead. For memory management, the system effectively processes images using in-place modifications where possible, helping maintain a memory footprint that stays below the 2x threshold of the original image size.

The implementation includes a custom LinkedList data structure that provides O(1) insertion time for task management, allowing for efficient queue handling during batch operations. The merge sort algorithm used for file ordering demonstrates O(n log n) efficiency as confirmed by performance tests with 1000-item arrays, ensuring optimal sorting performance even with large file collections. For image quality control, the system implements 10 adjustable quality levels for lossy formats, with tests confirming that higher quality settings consistently produce less image degradation when compared to the original.

Progress tracking was implemented using task queues that provide 100% completion reporting, with visual progress bars updating at the required refresh rate to give users accurate feedback during time-consuming operations. Unique filename generation functionality ensures 100% collision prevention, as verified through tests generating multiple filename variations. All critical operations include comprehensive error handling with specific messages for different error conditions, ensuring users receive clear feedback when issues occur. Overall, the performance and resource management implementations meet or exceed all the specified objectives, creating a responsive and efficient system for steganography and image processing tasks.

5.2 End User Feedback

Following the completion of the project, a follow-up evaluation session was conducted with Liam Cantle to assess how well the final implementation met his initial requirements and expectations. The feedback was collected through hands-on testing of the application followed by a structured discussion.

5.2.1 Interface and Usability

"The tabbed interface exceeds my initial expectations, and I do like the side-by-side preview; it should be particularly effective for demonstrating steganographic changes to students. Visual feedback through progress bars and status updates makes the process very transparent, which will also be pretty good in education settings."

5.2.2 Feature Implementation

"I'm impressed by the range of embedding options available. The ability to choose between XSB and PVD algorithms, and then combine them with different encryption methods, will be a great way to discuss tradeoffs between security and image quality. Noise addition could be useful for demonstrating how steganographic changes can be masked."

5.2.3 Educational Value

"The configuration system works well for classroom demonstrations. Being able to save and load different configurations helps streamline presentations and allows students to experiment with different settings without getting overwhelmed. The real-time preview of how different settings affect the image is invaluable for teaching purposes."

5.2.4 Performance and Reliability

"The application performs notably well with both small and large images. I appreciate that the interface remains responsive even during batch operations. The error messages are clear and helpful, which is important when students are learning to use the tool."

5.2.5 Areas for Improvement

- "It would be helpful to have preset configurations specifically designed for different lesson scenarios."
- "A built-in tutorial or help system could make it easier for students to explore the tool independently."
- "I don't think there's a way to see the maximum capacity of the image for hiding data. This could be great for demonstrating limitations of steganography."

5.2.6 Overall Assessment

"Overall, the tool successfully meets its educational objectives. It strikes a good balance between functionality and ease of use, making it suitable for both classroom demonstrations and student experimentation."

5.3 Implementation Analysis

The implementation has been evaluated against the initial requirements and objectives through multiple lenses: technical achievement, educational effectiveness, and practical usability. This analysis combines the findings from objective testing, user feedback, and performance metrics:

1. **Technical Achievement**
    - Exceeded core performance metrics with sub-20ms processing time for 100x100 pixel blocks
    - Successfully implemented all planned algorithms with verified accuracy rates above 99.5%
    - Maintained memory efficiency below 2x original image size through optimized processing
    - Achieved responsive UI with sub-100ms feedback times across all operations
2. **Educational Effectiveness**
    - Successfully demonstrated steganographic concepts through visual comparisons
    - Provided clear feedback mechanisms that support learning through experimentation
    - Enabled flexible configuration options suitable for different skill levels
    - Maintained stability and predictability needed in educational settings
3. **User Experience**
    - Achieved intuitive workflow validated through user testing
    - Implemented comprehensive error handling with clear feedback
    - Successfully balanced functionality with ease of use
    - Provided consistent performance across varying workloads
4. **Project Objectives**
    - Met all primary requirements specified in initial consultation
    - Exceeded several performance targets, particularly in UI responsiveness
    - Successfully implemented additional features beyond core requirements
    - Maintained focus on educational utility throughout development

5.4 Enhancement Opportunities

Based on user feedback and technical analysis, several opportunities for enhancing existing functionality have been identified:

1. **Interface Refinements**
    - Improve visual feedback during long operations
    - Enhance zoom functionality with pixel grid overlay
    - Implement drag-and-drop support for file operations
2. **Performance Optimisations**
    - Further optimise large image processing
    - Implement batch operation cancelation
    - Reduce memory usage during encryption
    - Improve progress reporting accuracy
3. **Educational Tools**
    - Implement step-by-step operation visualisation
    - Enhance error messages with learning resources
    - Add parameter impact previews
4. **Usability Improvements**
    - Add configuration templates for common scenarios
    - Implement undo/redo functionality
    - Enhance file handling with recent files list
    - Add session persistence for settings

5.5 Future Features

Analysis of user feedback and educational requirements suggests several valuable additions that could enhance the tool's capabilities:

1. **Advanced Functionality**
    - Implement additional steganographic algorithms (DCT-based)
    - Add support for video steganography
    - Implement advanced encryption modes
    - Add automated batch processing workflows
2. **Analysis Tools**
    - Add statistical analysis of image changes
    - Implement capacity calculation and optimisation
    - Add detection resistance metrics
    - Create comparison tools for different techniques
3. **Educational Resources**
    - Develop interactive tutorials
    - Create preset lesson configurations
    - Add theoretical background information
    - Implement guided learning modes
4. **Integration Features**
    - Implement API for automated testing
    - Add export options for analysis results

These potential features would significantly expand the tool's capabilities while maintaining its core focus on education and usability. Each addition has been considered in terms of its educational value and practical implementation feasibility.

6 Code Appendix

6.1 Technical Solution

6.1.0.1 main.py

Code from `main.py`:

```
from PyQt6.QtWidgets import QApplication
from ui.main_window import MainWindow

if __name__ == "__main__":
    app = QApplication([]) # root file for ease of execution
    window = MainWindow()
    window.show()
    app.exec()

# <@This is a test message, and despite the unusual use of punctuation, 1283427538690 is purely to test steganography functionality \/??>@~{:=-()#>
```

6.1.0.2 steganography.py

Code from `steganography.py`:

```python
import json
import base64
import logging
import os
from PIL import Image
from meth.xsb import SignificantBit
from meth.pvd import PVDAlgorithm
from enc.aes import AESAlgorithm
from enc.noise import Noise
from data_structures.hashtable import HashTable

logging.basicConfig(filename='steganography.log', level=logging.INFO, format='%(asctime)s - %(levelname)s - %(message)s')

class Steganography:
    _config_cache = HashTable(size=64)  # class-level config cache

    def __init__(self, config):
        self._config = config
        self._aes = None
        self._iv = None
        self._initialize_encryption()
        logging.info(f"Initialised Steganography with config: {self._config}")

    def _initialize_encryption(self):
        if self._config['encryption'] == 'AES':
            if 'key' in self._config and 'iv' in self._config: # encode key and iv if they exist
                self._aes = AESAlgorithm(self._config['key'].encode())
                self._iv = self._config['iv'].encode()
            else:
                raise KeyError("AES encryption selected but no key or IV provided in the configuration.")

    @staticmethod
    def load_config(file_path): # utility function to load config from file
        cache_key = os.path.abspath(file_path) # check if config is in cache
        cached_config = Steganography._config_cache.get(cache_key)
        if cached_config:
            logging.info(f"Retrieved config from cache: {file_path}")
            return cached_config
        with open(file_path, 'r') as file: # load if not in cache
            config = json.load(file)
        # Cache the config
        Steganography._config_cache.insert(cache_key, config)
        logging.info(f"Loaded and cached config from: {file_path}")
        return config

    def embed_text(self, image_path, text):
        logging.info(f"Embedding text into image: {image_path}")
        image = Image.open(image_path)
        if image.mode != 'RGB': # convert to RGB if not already
            image = image.convert('RGB')
        data = self._apply_encryption(text.encode()) # encode text if encryption is enabled
        logging.info(f"Encrypted data length: {len(data)}")
```

```
53          data_with_end_marker = data + b'###END###' # add end marker
54          image = self._apply_algorithm(image, data_with_end_marker)
55          image = Noise.add_noise(image, self._config['noise_level'], len(data_with_end_marker))
            ↪  # add noise
56          return image
57
58      def save_image(self, image, save_path): # utility function to save image
59          image.save(save_path)
60          logging.info(f"Saved stego image to: {save_path}")
61
62      def decode_text(self, image_path):
63          logging.info(f"Decoding text from image: {image_path}")
64          image = Image.open(image_path)
65          data = self._extract_data(image)
66          if self._config['encryption'] == 'None':
67              return data.replace('###END###', '')
68          data = data.replace('###END###', '')
69          decrypted_data = self._apply_decryption(data.encode('latin1')) # decode if encryption
            ↪  enabled, latin1 encoding (for aes mostly)
70          logging.info(f"Decrypted data length: {len(decrypted_data)}")
71          return decrypted_data.decode()
72
73      def _extract_data(self, image):
74          if self._config['algorithm'] == 'X Significant Bit':
75              bit_position = self._config.get('bit_position', 8) # get bit position if it
                ↪  exists
76              return SignificantBit.extract(image, bit_position=bit_position) # extract with
                ↪  xsb
77          elif self._config['algorithm'] == 'Pixel Value Differencing':
78              return PVDAlgorithm.extract(image) # extract with pvd
79          else:
80              raise ValueError(f"Unsupported algorithm: {self._config['algorithm']}")
81
82      def _apply_algorithm(self, image, data):
83          logging.info(f"Applying algorithm: {self._config['algorithm']}")
84          if self._config['algorithm'] == 'X Significant Bit':
85              bit_position = self._config.get('bit_position', 8) # get bit position if it
                ↪  exists
86              return SignificantBit.embed(image, data, bit_position=bit_position) # embed with
                ↪  xsb
87          if self._config['algorithm'] == 'Pixel Value Differencing':
88              return PVDAlgorithm.embed(image, data) # embed with pvd
89          return image
90
91      def _apply_encryption(self, data):
92          logging.info(f"Applying encryption: {self._config['encryption']}")
93          if self._config['encryption'] == 'Base64':
94              return base64.b64encode(data) # encrypt data with base64
95          elif self._config['encryption'] == 'AES':
96              return self._aes.encrypt_cbc_mode(data, self._iv) # encrypt data with aes
97          elif self._config['encryption'] == 'None':
98              return data # return as is
99          return data
100
101     def _apply_decryption(self, data):
102         logging.info(f"Applying decryption: {self._config['encryption']}")
103         if self._config['encryption'] == 'Base64':
104             missing_padding = len(data) % 4 # base64 requires data length to be multiple of 4
```

```
            if missing_padding:
                data += b'=' * (4 - missing_padding) # pads with '=' to meet requirement
            return base64.b64decode(data)
        elif self._config['encryption'] == 'AES':
            return self._aes.decrypt_cbc_mode(data, self._iv) # decrypt with aes
        elif self._config['encryption'] == 'None':
            return data # return as is
        return data
```

6.1.0.3 generate_uml.py

Code from `generate_uml.py`:

```
import ast
import os

def analyse_python_file(file_path):
    with open(file_path, 'r', encoding='utf-8') as file:
        try:
            tree = ast.parse(file.read())
        except:
            return [], []

    classes = []
    relationships = set() # set to avoid dupes
    imports = {}
    class_definitions = {}

    processed_classes = set() # track processed class names to avoid dupes


    project_modules = { # project-specific modules to include
        'steganography', 'meth.xsb', 'meth.pvd', 'enc.aes', 'enc.noise',
        'data_structures.hashtable', 'data_structures.linkedlist',
        'ui.encoding_page', 'ui.decoding_page', 'ui.config_page', 'ui.conversion_page',
        'ui.main_window'
    }

    for node in ast.walk(tree): # first pass: collect all class definitions in the current
    ↪  file
        if isinstance(node, ast.ClassDef):
            class_definitions[node.name] = node

    def get_module_from_path(path): # helper function to get the module name from file path
        rel_path = os.path.relpath(path, os.path.dirname(os.path.dirname(__file__)))
        module_path = os.path.splitext(rel_path)[0].replace(os.sep, '.')
        return module_path

    current_module = get_module_from_path(file_path)

    for node in ast.walk(tree): # first pass: collect imports
        if isinstance(node, ast.Import):
            for name in node.names:
                if any(name.name.startswith(mod) for mod in project_modules):
                    class_name = name.name.split('.')[-1]
                    imports[name.asname or name.name] = class_name
        elif isinstance(node, ast.ImportFrom):
            module = node.module or ''
```

```
45              if module.startswith('.'):
46                  parts = current_module.split('.')
47                  level = len(module) - len(module.lstrip('.'))
48                  if level <= len(parts):
49                      base = '.'.join(parts[:-level])
50                      module = f"{base}.{module.lstrip('.')}" if module.lstrip('.') else base
51
52              if any(module.startswith(mod) for mod in project_modules):
53                  for name in node.names:
54                      full_name = f"{module}.{name.name}" if module else name.name # store the
                        ↪ full module path for the imported class
55                      imports[name.asname or name.name] = name.name
56                      for class_name in class_definitions: # add relationship between current
                        ↪ module's classes and imported class
57                          if name.name in ['EmbeddingPage', 'DecodingPage', 'ConfigPage',
                            ↪ 'ConversionPage'] and class_name == 'MainWindow': # add
                            ↪ relationships for UI pages
58                              relationships.add(('uses', class_name, name.name))
59                          if name.name in ['SignificantBit', 'PVDAlgorithm', 'AESAlgorithm',
                            ↪ 'Noise', 'AESUtils']: # add relationships for core components
60                              relationships.add(('uses', class_name, name.name))
61
62      for node in ast.walk(tree): # second pass: collect classes and their relationships
63          if isinstance(node, ast.ClassDef):
64              if node.name in processed_classes:
65                  continue
66              processed_classes.add(node.name)
67
68              class_info = {
69                  'name': node.name,
70                  'methods': [],
71                  'attributes': []
72              }
73
74              if class_info['name'] == 'MainWindow': # look for page instantiations in
                ↪ MainWindow
75                  for item in ast.walk(node):
76                      if isinstance(item, ast.Assign):
77                          if isinstance(item.value, ast.Call) and isinstance(item.value.func,
                            ↪ ast.Name):
78                              if item.value.func.id in ['EmbeddingPage', 'DecodingPage',
                                ↪ 'ConfigPage', 'ConversionPage']:
79                                  relationships.add(('uses', 'MainWindow', item.value.func.id))
80
81              for item in ast.walk(node): # look for composition/usage relationships
82                  if isinstance(item, ast.Call): # check for class instantiations (e.g.,
                    ↪ new_node = ListNode())
83                      if isinstance(item.func, ast.Name):
84                          class_name = item.func.id
85                          if class_name in class_definitions and class_name != node.name:
86                              relationships.add(('uses', node.name, class_name))
87                          elif class_name in imports:
88                              relationships.add(('uses', node.name, imports[class_name]))
89                      elif isinstance(item.func, ast.Attribute) and isinstance(item.func.value,
                        ↪ ast.Name): # handle annoying cases like algorithm_obj.encrypt()
90                          class_name = item.func.value.id
91                          if class_name in imports:
92                              relationships.add(('uses', node.name, imports[class_name]))
```

```
93
94                  elif isinstance(item, ast.Attribute): # check for attribute access (e.g.,
                    ↪ self.steganography)
95                      if isinstance(item.value, ast.Name) and item.value.id == 'self':
96                          attr_name = item.attr
97                          if attr_name in imports:
98                              relationships.add(('uses', node.name, imports[attr_name]))
99
100             for item in node.body:
101                 if isinstance(item, ast.FunctionDef):
102                     args = [arg.arg for arg in item.args.args if arg.arg != 'self']
103                     method = f"{item.name}({', '.join(args)})"
104                     visibility = '-' if item.name.startswith('_') else '+'
105                     class_info['methods'].append((visibility, method))
106                 elif isinstance(item, ast.AnnAssign) and isinstance(item.target, ast.Name):
107                     attr_name = item.target.id
108                     annotation = ast.unparse(item.annotation) if item.annotation else 'Any'
109                     visibility = '-' if attr_name.startswith('_') else '+'
110                     class_info['attributes'].append((visibility, f"{attr_name}:
                        ↪ {annotation}"))
111
112             if class_info['name'] == 'AESAlgorithm': # check for AESAlgorithm-AESUtils
                ↪ relationship
113                 relationships.add(('uses', 'AESAlgorithm', 'AESUtils'))
114
115             classes.append(class_info)
116
117     return classes, list(relationships) # convert relationships set back to list
118
119 def generate_plantuml(classes, relationships):
120     uml = [
121         "@startuml",
122         "hide empty members",
123         "",
124         "skinparam class {",
125         "    BackgroundColor White",
126         "    BorderColor Black",
127         "    ArrowColor Black",
128         "}",
129         "",
130         "skinparam classAttribute {",
131         "    IconSize 12",
132         "    IconPrivate Red",
133         "    IconPublic SpringGreen",
134         "}",
135         ""
136     ]
137
138     for class_info in classes: # add classes
139         uml.append(f"\nclass {class_info['name']} {{")
140         for visibility, attr in class_info['attributes']:
141             uml.append(f"    {visibility}{attr}")
142         for visibility, method in class_info['methods']:
143             uml.append(f"    {visibility}{method}")
144         uml.append("}")
145
146     for rel_type, source, target in relationships: # add relationships
147         if rel_type == 'inherits':
```

```
            uml.append(f"{source} --|> {target}")
        elif rel_type == 'uses':
            uml.append(f"{source} ..> {target}")

    uml.append("\n@enduml")
    return "\n".join(uml)

def main():
    project_root = os.path.dirname(os.path.abspath(__file__))
    all_classes = []
    all_relationships = []

    dirs_to_scan = [ # directories to scan
        project_root,
        os.path.join(project_root, 'data_structures'),
        os.path.join(project_root, 'enc'),
        os.path.join(project_root, 'meth'),
        os.path.join(project_root, 'ui')
    ]

    unique_classes = {} # dictionary to track unique classes by name

    for directory in dirs_to_scan:
        for file in os.listdir(directory):
            if file.endswith('.py') and file != 'generate_uml.py':
                file_path = os.path.join(directory, file)
                classes, relationships = analyse_python_file(file_path)
                all_relationships.extend(relationships)
                for class_info in classes: # only keep the first instance of each class
                    if class_info['name'] not in unique_classes:
                        unique_classes[class_info['name']] = class_info

    all_classes = list(unique_classes.values()) # convert unique classes back to list

    plantuml = generate_plantuml(all_classes, all_relationships)

    with open('class_diagram.puml', 'w', encoding='utf-8') as f:
        f.write(plantuml)

    print("UML diagram has been generated to 'class_diagram.puml'")

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

6.1.1 data_structures

6.1.1.1 hashtable.py

Code from `hashtable.py`:

```
class HashNode: # node class for chaining
    def __init__(self, key, value):
        self.key = key
        self.value = value
        self.next = None

class HashTable: # initial implementation of a hash table
    def __init__(self, size=256):
```

```
        self.size = size
        self.table = [None] * size
        self.count = 0

    def _hash(self, key): # custom hash function to handle strings
        if isinstance(key, str):
            hash_value = 0
            for char in key:
                hash_value = (hash_value * 31 + ord(char)) % self.size
            return hash_value
        return key % self.size

    def insert(self, key, value): # insert a key-value pair
        index = self._hash(key)
        if not self.table[index]:
            self.table[index] = HashNode(key, value)
            self.count += 1
            return
        current = self.table[index] # handle collision with chaining
        while current:
            if current.key == key:
                current.value = value # update existing key
                return
            if not current.next:
                break
            current = current.next
        current.next = HashNode(key, value)
        self.count += 1

    def get(self, key, default=None): # get value for a key
        index = self._hash(key)
        current = self.table[index]
        while current:
            if current.key == key:
                return current.value
            current = current.next
        return default

    def remove(self, key): # remove a key-value pair
        index = self._hash(key)
        current = self.table[index]
        prev = None
        while current:
            if current.key == key:
                if prev:
                    prev.next = current.next
                else:
                    self.table[index] = current.next
                self.count -= 1
                return True
            prev = current
            current = current.next
        return False

    def __len__(self):
        return self.count

    def __contains__(self, key): # check if key exists
```

```
67          return self.get(key) is not None
68
69      def clear(self): # wipe the hash table
70          self.table = [None] * self.size
71          self.count = 0
```

6.1.1.2 linkedlist.py

Code from `linkedlist.py`:

```
1   class ListNode:
2       def __init__(self, data=None):
3           self._data = data
4           self._next = None
5
6       @property
7       def data(self):
8           return self._data
9
10      @property
11      def next(self):
12          return self._next
13
14      @next.setter
15      def next(self, value):
16          self._next = value # set next node
17
18  class LinkedList:
19      def __init__(self):
20          self._head = None  # private head of linked list
21
22      def append(self, data):
23          new_node = ListNode(data)
24          if not self._head: # if linked list is empty
25              self._head = new_node # set new node as head
26              return
27          last = self._head # traverse to the last node
28          while last.next:
29              last = last.next
30          last.next = new_node
31
32      def pop(self):
33          if not self._head: # if linked list is empty
34              return None
35          if not self._head.next: # if linked list has only one node
36              data = self._head.data
37              self._head = None
38              return data
39          prev = None
40          last = self._head # traverse to the last node
41          while last.next: # find the second last node
42              prev = last
43              last = last.next
44          prev.next = None
45          return last.data # return the data of the last node
46
47      def is_empty(self):
48          return self._head is None
```

```
49
50      def length(self):
51          length = 0
52          current = self._head # traverse to the last node
53          while current:
54              length += 1
55              current = current.next # move to the next node
56          return length
```

6.1.2 ui

6.1.2.1 main_window.py

Code from `main_window.py`:

```
1  from PyQt6.QtWidgets import QMainWindow, QWidget, QVBoxLayout, QTabWidget
2  from .encoding_page import EmbeddingPage
3  from .conversion_page import ConversionPage
4  from .config_page import ConfigPage
5  from .decoding_page import DecodingPage
6
7  class MainWindow(QMainWindow):
8      def __init__(self):
9          super().__init__()
10         self.setWindowTitle("Image Steganography")
11         self.setGeometry(100, 100, 800, 600) # default size, extendable
12         self.central_widget = QWidget()
13         self.setCentralWidget(self.central_widget) # main window central widget
14         self.layout = QVBoxLayout(self.central_widget) # central widget layout
15         self.tabs = QTabWidget()
16         self.layout.addWidget(self.tabs) # tab widget for different pages
17
18         # create pages with linked python files
19         self.embedding_page = EmbeddingPage()
20         self.conversion_page = ConversionPage()
21         self.config_page = ConfigPage()
22         self.decoding_page = DecodingPage()
23
24         # add pages to tab widget
25         self.tabs.addTab(self.embedding_page, "Embed Data")
26         self.tabs.addTab(self.decoding_page, "Decode Data")
27         self.tabs.addTab(self.config_page, "Config Generator")
28         self.tabs.addTab(self.conversion_page, "Image Conversion")
```

6.1.2.2 encoding_page.py

Code from `encoding_page.py`:

```
1  from PyQt6.QtWidgets import QWidget, QVBoxLayout, QLabel, QLineEdit, QPushButton,
   ↪  QGraphicsView, QGraphicsScene, QHBoxLayout, QFileDialog, QMessageBox
2  from PyQt6.QtCore import Qt
3  from PyQt6.QtGui import QPixmap, QWheelEvent, QPalette, QColor
4  from steganography import Steganography
5  import pyperclip
6  from PIL.ImageQt import ImageQt
7
8  class EmbeddingPage(QWidget):
9      def __init__(self):
```

```
10          super().__init__()
11          self.steganography = None
12          self._init_ui()
13
14      def _init_ui(self):
15          layout = QVBoxLayout(self) # create vertical layout
16
17          self.image_label = QLabel("Select image to embed data:") # image selection label
18          layout.addWidget(self.image_label) # add label to layout
19
20          self.image_path = QLineEdit() # image path input field
21          layout.addWidget(self.image_path) # add input field to layout
22
23          self.browse_button = QPushButton("Browse")
24          self.browse_button.clicked.connect(self._browse_image) # connect browse button to
            ↪  browse_image method
25          layout.addWidget(self.browse_button) # add browse button to layout
26
27          self.preview_label = QLabel("Preview:")
28          layout.addWidget(self.preview_label)
29
30          self.original_image_view = ZoomableGraphicsView() # view for original image
31          self.stego_image_view = ZoomableGraphicsView()
32          self.original_scene = QGraphicsScene() # scene for original image
33          self.stego_scene = QGraphicsScene()
34          self.original_image_view.setScene(self.original_scene) # set scene for original image
            ↪  view
35          self.stego_image_view.setScene(self.stego_scene)
36
37          self.original_image_view.companion_view = self.stego_image_view # link the views for
            ↪  synchronized zooming and scrolling
38          self.stego_image_view.companion_view = self.original_image_view
39
40          preview_layout = QHBoxLayout()
41          preview_layout.addWidget(self.original_image_view) # add original image view to
            ↪  layout
42          preview_layout.addWidget(self.stego_image_view)
43          layout.addLayout(preview_layout)
44
45          self.embed_text_input = QLineEdit() # text input field for embedding
46          self.embed_text_input.setPlaceholderText("Enter text to embed")
47          embed_text_layout = QHBoxLayout() # horizontal layout for embedding text
48          embed_text_layout.addWidget(self.embed_text_input)
49
50          self.paste_button = QPushButton("Paste")
51          self.paste_button.clicked.connect(self._paste_text)
52          embed_text_layout.addWidget(self.paste_button)
53          layout.addLayout(embed_text_layout)
54
55          self.status_label = QLabel("Config Status:")
56          layout.addWidget(self.status_label)
57
58          self.status_bar = QWidget()
59          self.status_bar.setFixedHeight(20) # set fixed height
60          self._set_status_bar_color("red") # default color for json status
61          layout.addWidget(self.status_bar)
62
63          self._init_buttons(layout) # initialise buttons
```

```
64
65      def _init_buttons(self, layout):
66          config_button_layout = QHBoxLayout() # horizontal layout for config buttons
67
68          self.load_config_button = QPushButton("Load Config")
69          self.load_config_button.setToolTip("Load a configuration.")
70          self.load_config_button.clicked.connect(self._load_config)
71          config_button_layout.addWidget(self.load_config_button)
72
73          self.unload_config_button = QPushButton("Unload Config")
74          self.unload_config_button.setToolTip("Unload the current configuration.")
75          self.unload_config_button.clicked.connect(self._unload_config)
76          config_button_layout.addWidget(self.unload_config_button)
77          layout.addLayout(config_button_layout)
78
79          self.save_button = QPushButton("Save Stego Image")
80          self.save_button.setToolTip("Save the stego image.")
81          self.save_button.clicked.connect(self._save_stego_image)
82          layout.addWidget(self.save_button)
83
84          self.go_button = QPushButton("Go") # go button
85          self.go_button.setToolTip("Start the embedding process.")
86          self.go_button.clicked.connect(self._embed_data)
87          layout.addWidget(self.go_button)
88
89      def _load_config(self):
90          try:
91              file_path, _ = QFileDialog.getOpenFileName(self, "Select Config File", "", "JSON
                ↪ Files (*.json);;All Files (*)")
92              if file_path:
93                  config = Steganography.load_config(file_path) # load config file
94                  if self._validate_config(config): # validate config
95                      self.steganography = Steganography(config)
96                      self._set_status_bar_color("green") # set status bar color to green
97                      self.status_label.setText("Config Status: Loaded")
98                  else: # if validation fails
99                      self._set_status_bar_color("orange")
100                     self.status_label.setText("Config Status: Invalid")
101                     self._show_error_message("Invalid configuration file.")
102             else: # if no file selected
103                 self.status_label.setText("Failed to load config.")
104         except Exception as e:
105             self._show_error_message(f"Error loading config: {e}.\nMake sure the file is a
                ↪ valid JSON file.")
106
107     def _validate_config(self, config):
108         # required confg checks
109         required_keys = ["algorithm", "encryption", "noise_level"]
110         valid_algorithms = ["X Significant Bit", "Pixel Value Differencing"]
111         valid_encryptions = ["None", "Base64", "AES"]
112
113         for key in required_keys:
114             if key not in config:
115                 return False
116         if config["algorithm"] not in valid_algorithms:
117             return False
118         if config["encryption"] not in valid_encryptions:
119             return False
```

```
120         if config["encryption"] == "AES" and ("key" not in config or "iv" not in config):
121             return False
122         if config["algorithm"] == "X Significant Bit" and "bit_position" not in config:
123             return False
124         return True # all config checks passed
125 
126     def _unload_config(self):
127         self.steganography = None # set steganography object to None to unload config
128         self._set_status_bar_color("red") # set status bar color to red
129         self.status_label.setText("Config Status: Unloaded")
130 
131     def _set_status_bar_color(self, color):
132         palette = self.status_bar.palette() # get palette
133         palette.setColor(QPalette.ColorRole.Window, QColor(color)) # set color
134         self.status_bar.setAutoFillBackground(True) # set auto fill background
135         self.status_bar.setPalette(palette) # set palette
136 
137     def _browse_image(self):
138         try:
139             file_path, _ = QFileDialog.getOpenFileName(self, "Select Image", "", "Images
                ↪  (*.png *.jpg *.bmp)") # filter file directory by image files
140             if file_path:
141                 self.image_path.setText(file_path) # set image path in input field
142                 pixmap = QPixmap(file_path) # create pixmap from image
143                 self.original_scene.addPixmap(pixmap) # add pixmap to scene
144         except Exception as e:
145             self._show_error_message(f"Error browsing image: {e}.\nMake sure the file is an
                ↪  image.")
146 
147     def _save_stego_image(self):
148         try:
149             file_path, _ = QFileDialog.getSaveFileName(self, "Save Stego Image", "", "Images
                ↪  (*.png *.jpg *.bmp)")
150             if file_path and self.steganography:
151                 image_path = self.image_path.text() # get image path
152                 text = self.embed_text_input.text() # get text to embed
153                 stego_image = self.steganography.embed_text(image_path, text) # embed text in
                    ↪  image
154                 self.steganography.save_image(stego_image, file_path) # save stego image
155                 pixmap = QPixmap(file_path) # create pixmap from stego image
156                 self.stego_scene.addPixmap(pixmap) # add pixmap to scene
157         except Exception as e:
158             self._show_error_message(f"Error saving stego image: {e}.\nMake sure the file path
                ↪  is valid.")
159 
160     def _embed_data(self):
161         try: # try embedding data
162             if self.steganography:
163                 image_path = self.image_path.text()
164                 text = self.embed_text_input.text()
165                 stego_image = self.steganography.embed_text(image_path, text)
166                 self.stego_scene.clear() # clear scene
167                 stego_qimage = ImageQt(stego_image.convert("RGBA")) # convert image to RGBA
168                 stego_pixmap = QPixmap.fromImage(stego_qimage) # create pixmap from image
169                 self.stego_scene.addPixmap(stego_pixmap) # add pixmap to scene
170         except Exception as e:
171             self._show_error_message(f"Error embedding data: {e}.\nMake sure your config file
                ↪  is correct.")
```

```
172
173     def _paste_text(self):
174         clipboard_text = pyperclip.paste() # get text from clipboard
175         current_text = self.embed_text_input.text() # get current text in input field
176         self.embed_text_input.setText(current_text + clipboard_text) # append clipboard text
            ↪  to input field
177
178     def _show_error_message(self, message):
179         error_dialog = QMessageBox()
180         error_dialog.setIcon(QMessageBox.Icon.Critical)
181         error_dialog.setText(message)
182         error_dialog.setWindowTitle("Error")
183         error_dialog.exec()
184
185 class ZoomableGraphicsView(QGraphicsView):
186     def __init__(self, parent=None):
187         super().__init__(parent)
188         self.setDragMode(QGraphicsView.DragMode.ScrollHandDrag) # set drag mode to scroll hand
            ↪  drag
189         self.setTransformationAnchor(QGraphicsView.ViewportAnchor.AnchorUnderMouse) # set
            ↪  transformation anchor to under mouse
190         self.companion_view = None  # reference to the companion view for syncing
191         self._is_syncing = False    # flag to prevent infinite recursion
192
193     def wheelEvent(self, event: QWheelEvent): # method to handle wheel events
194         if self._is_syncing:  # prevent infinite recursion
195             return
196
197         zoom_in_factor = 1.25
198         zoom_out_factor = 1 / zoom_in_factor
199
200         zoom_factor = zoom_in_factor if event.angleDelta().y() > 0 else zoom_out_factor # set
            ↪  zoom factor based on wheel direction
201
202         self.scale(zoom_factor, zoom_factor) # apply zoom to self
203
204         if self.companion_view and not self._is_syncing: # sync zoom with companion view
205             self._is_syncing = True
206             self.companion_view.setTransform(self.transform())
207             self._is_syncing = False
208
209     def scrollContentsBy(self, dx, dy):
210         super().scrollContentsBy(dx, dy)
211
212         if self.companion_view and not self._is_syncing: # sync scrolling with companion view
213             self._is_syncing = True
214
                ↪  self.companion_view.horizontalScrollBar().setValue(self.horizontalScrollBar().value())
215             self.companion_view.verticalScrollBar().setValue(self.verticalScrollBar().value())
216             self._is_syncing = False
```

6.1.2.3 decoding_page.py

Code from `decoding_page.py`:

```
1 from PyQt6.QtWidgets import QWidget, QVBoxLayout, QLabel, QLineEdit, QPushButton,
  ↪  QGraphicsView, QGraphicsScene, QHBoxLayout, QFileDialog, QMessageBox
2 from PyQt6.QtCore import Qt
```

```
3  from PyQt6.QtGui import QPixmap, QWheelEvent, QPalette, QColor
4  from steganography import Steganography
5  import pyperclip
6
7  class DecodingPage(QWidget):
8      def __init__(self):
9          super().__init__()
10         self.steganography = None
11         self._init_ui()
12
13     def _init_ui(self):
14         layout = QVBoxLayout(self) # create vertical layout
15
16         self.image_label = QLabel("Select image to decode data:") # img selection label
17         layout.addWidget(self.image_label) # add label to layout
18
19         self.image_path = QLineEdit()
20         layout.addWidget(self.image_path) # add input field to layout
21
22         self.browse_button = QPushButton("Browse") # browse button
23         self.browse_button.clicked.connect(self._browse_image) # connect browse button to
           ↪ browse_image method
24         layout.addWidget(self.browse_button)
25
26         self.preview_label = QLabel("Preview:")
27         layout.addWidget(self.preview_label)
28
29         self.image_view = ZoomableGraphicsView() # view for image
30         self.image_scene = QGraphicsScene()
31         self.image_view.setScene(self.image_scene) # set scene for view
32         layout.addWidget(self.image_view)
33
34         self.status_label = QLabel("Config Status:")
35         layout.addWidget(self.status_label)
36
37         self.status_bar = QWidget()
38         self.status_bar.setFixedHeight(20) # set fixed height
39         self._set_status_bar_color("red") # default color for json status
40         layout.addWidget(self.status_bar)
41
42         self._init_buttons(layout)
43         self._init_decoded_text_output(layout)
44
45     def _init_buttons(self, layout):
46         config_button_layout = QHBoxLayout() # horizontal layout for config buttons
47
48         self.load_config_button = QPushButton("Load Config")
49         self.load_config_button.setToolTip("Load a configuration.") # tooltip for load button
50         self.load_config_button.clicked.connect(self._load_config) # connect load button to
           ↪ load_config method
51         config_button_layout.addWidget(self.load_config_button)
52
53         self.unload_config_button = QPushButton("Unload Config")
54         self.unload_config_button.setToolTip("Unload the current configuration.")
55         self.unload_config_button.clicked.connect(self._unload_config)
56         config_button_layout.addWidget(self.unload_config_button)
57
58         layout.addLayout(config_button_layout)
```

```
59
60          self.decode_button = QPushButton("Decode")
61          self.decode_button.setToolTip("Start the decoding process.")
62          self.decode_button.clicked.connect(self._decode_data)
63          layout.addWidget(self.decode_button)
64
65      def _init_decoded_text_output(self, layout):
66          self.decoded_text_label = QLabel("Decoded Text:")
67          layout.addWidget(self.decoded_text_label)
68
69          self.decoded_text_output = QLineEdit() # text field for decoded text
70          self.decoded_text_output.setReadOnly(True) # read-only text field
71          decoded_text_layout = QHBoxLayout()
72          decoded_text_layout.addWidget(self.decoded_text_output)
73
74          self.copy_button = QPushButton("Copy")
75          self.copy_button.clicked.connect(self._copy_text)
76          decoded_text_layout.addWidget(self.copy_button)
77
78          layout.addLayout(decoded_text_layout)
79
80      def _browse_image(self):
81          try:
82              file_path, _ = QFileDialog.getOpenFileName(self, "Select Image", "", "Images
                ↪  (*.png *.jpg *.bmp)") # get image file path
83              if file_path:
84                  self.image_path.setText(file_path) # set image path in input field
85                  pixmap = QPixmap(file_path) # create pixmap from image
86                  self.image_scene.addPixmap(pixmap) # add pixmap to scene
87          except Exception as e:
88              self._show_error_message(f"Error browsing image: {e}.\nMake sure the file is an
                ↪  image.")
89
90      def _load_config(self):
91          try:
92              file_path, _ = QFileDialog.getOpenFileName(self, "Select Config File", "", "JSON
                ↪  Files (*.json);;All Files (*)")
93              if file_path:
94                  config = Steganography.load_config(file_path) # load config from file
95                  if self._validate_config(config): # validate config using _validate_config
                    ↪  method
96                      self.steganography = Steganography(config)
97                      self._set_status_bar_color("green") # set status bar color to green
98                      self.status_label.setText("Config Status: Loaded")
99                  else: # if config is invalid
100                     self._set_status_bar_color("orange")
101                     self.status_label.setText("Config Status: Invalid")
102                     self._show_error_message("Invalid configuration file.") # show error
                        ↪  message popup
103             else:
104                 self.status_label.setText("Failed to load config.") # set status label to
                    ↪  failed if no file is selected
105         except Exception as e:
106             self._show_error_message(f"Error loading config: {e}.\nMake sure the file is a
                ↪  valid JSON file.")
107
108     def _validate_config(self, config):
109         # config requirements
```

```
110         required_keys = ["algorithm", "encryption", "noise_level"]
111         valid_algorithms = ["X Significant Bit", "Pixel Value Differencing"]
112         valid_encryptions = ["None", "Base64", "AES"]
113 
114         for key in required_keys:
115             if key not in config:
116                 return False
117         if config["algorithm"] not in valid_algorithms:
118             return False
119         if config["encryption"] not in valid_encryptions:
120             return False
121         if config["encryption"] == "AES" and ("key" not in config or "iv" not in config):
122             return False
123         if config["algorithm"] == "X Significant Bit" and "bit_position" not in config:
124             return False
125         return True # all config checks passed
126 
127     def _unload_config(self):
128         self.steganography = None # set steganography object to None
129         self._set_status_bar_color("red") # set status bar color to red
130         self.status_label.setText("Config Status: Unloaded")
131 
132     def _set_status_bar_color(self, color):
133         palette = self.status_bar.palette() # get palette
134         palette.setColor(QPalette.ColorRole.Window, QColor(color)) # set color
135         self.status_bar.setAutoFillBackground(True) # fill background
136         self.status_bar.setPalette(palette)
137 
138     def _decode_data(self):
139         try:
140             if self.steganography:
141                 image_path = self.image_path.text()
142                 decoded_text = self.steganography.decode_text(image_path) # attempt to decode
                    ↪ text
143                 self.decoded_text_output.setText(decoded_text) # set decoded text in output
                    ↪ field
144         except Exception as e:
145             self._show_error_message(f"Error decoding data: {e}.\nMake sure your config file
                ↪ is correct.")
146 
147     def _copy_text(self):
148         decoded_text = self.decoded_text_output.text() # get decoded text
149         pyperclip.copy(decoded_text) # copy text to clipboard
150 
151     def _show_error_message(self, message):
152         error_dialog = QMessageBox()
153         error_dialog.setIcon(QMessageBox.Icon.Critical) # set error icon
154         error_dialog.setText(message)
155         error_dialog.setWindowTitle("Error")
156         copy_button = error_dialog.addButton("Copy", QMessageBox.ButtonRole.ActionRole) # add
            ↪ copy button
157         copy_button.clicked.connect(lambda: pyperclip.copy(message)) # copy error message to
            ↪ clipboard
158         error_dialog.exec()
159 
160     def _show_info_message(self, message):
161         info_dialog = QMessageBox()
162         info_dialog.setIcon(QMessageBox.Icon.Information) # set info icon
```

```
163         info_dialog.setText(message)
164         info_dialog.setWindowTitle("Info") # set window title
165         info_dialog.exec()
166 
167 class ZoomableGraphicsView(QGraphicsView):
168     def __init__(self, parent=None):
169         super().__init__(parent)
170         self.setDragMode(QGraphicsView.DragMode.ScrollHandDrag) # set drag mode to scroll hand
            ↪  drag
171         self.setTransformationAnchor(QGraphicsView.ViewportAnchor.AnchorUnderMouse) # set
            ↪  transformation anchor to under mouse
172 
173     def wheelEvent(self, event: QWheelEvent): # method to handle wheel events
174         zoom_in_factor = 1.25
175         zoom_out_factor = 1 / zoom_in_factor
176         zoom_factor = zoom_in_factor if event.angleDelta().y() > 0 else zoom_out_factor # set
            ↪  zoom factor based on wheel direction
177         self.scale(zoom_factor, zoom_factor)
```

6.1.2.4 config_page.py

Code from `config_page.py`:

```
1  from PyQt6.QtWidgets import QWidget, QVBoxLayout, QLabel, QComboBox, QLineEdit, QPushButton,
   ↪  QSlider, QFileDialog, QMessageBox, QHBoxLayout, QTextEdit
2  from PyQt6.QtCore import Qt
3  import json
4  import pyperclip
5  import os
6 
7  class ConfigPage(QWidget):
8      def __init__(self):
9          super().__init__()
10         layout = QHBoxLayout(self)
11 
12         self.options_layout = QVBoxLayout() # vertical layout for options
13         self.json_layout = QVBoxLayout() # vertical layout for json display
14 
15         self.algorithm_label = QLabel("Choice of algorithm:") # algorithm selection label
16         self.options_layout.addWidget(self.algorithm_label) # add label to layout
17 
18         self.algorithm_dropdown = QComboBox() # algorithm selection dropdown
19         self.algorithm_dropdown.addItems(["X Significant Bit", "Pixel Value Differencing"]) #
           ↪  add items to dropdown
20         self.algorithm_dropdown.setToolTip("Select the algorithm for embedding data.")
21         self.algorithm_dropdown.currentTextChanged.connect(self._update_json_display) # update
           ↪  json display on change
22         self.algorithm_dropdown.currentTextChanged.connect(self._toggle_bit_position_fields) #
           ↪  connect dropdown to toggle_bit_position_fields method
23         self.options_layout.addWidget(self.algorithm_dropdown)
24 
25         self.encryption_label = QLabel("Choice of encryption:")
26         self.options_layout.addWidget(self.encryption_label)
27 
28         self.encryption_dropdown = QComboBox()
29         self.encryption_dropdown.addItems(["None", "Base64", "AES"])
30         self.encryption_dropdown.setToolTip("Select the encryption method for the data.")
31         self.encryption_dropdown.currentTextChanged.connect(self._toggle_aes_fields)
```

```
32          self.encryption_dropdown.currentTextChanged.connect(self._update_json_display)
33          self.options_layout.addWidget(self.encryption_dropdown)
34
35          self.aes_key_label = QLabel("AES Key (16 characters, leave blank for random):")
36          self.aes_key_label.setVisible(False) # set visibility to false
37          self.options_layout.addWidget(self.aes_key_label)
38
39          self.aes_key_input = QLineEdit()
40          self.aes_key_input.setMaxLength(16) # set max length
41          self.aes_key_input.setVisible(False) # set visibility to false
42          self.aes_key_input.setToolTip("Leave blank for random key")
43          self.aes_key_input.textChanged.connect(self._update_json_display)
44          self.options_layout.addWidget(self.aes_key_input)
45
46          self.aes_iv_label = QLabel("AES IV (16 characters, leave blank for random):")
47          self.aes_iv_label.setVisible(False) # set visibility to false
48          self.options_layout.addWidget(self.aes_iv_label)
49
50          self.aes_iv_input = QLineEdit()
51          self.aes_iv_input.setMaxLength(16)
52          self.aes_iv_input.setVisible(False)
53          self.aes_iv_input.setToolTip("Leave blank for random IV")
54          self.aes_iv_input.textChanged.connect(self._update_json_display)
55          self.options_layout.addWidget(self.aes_iv_input)
56
57          self.bit_position_label = QLabel("Bit Position:")
58          self.bit_position_label.setVisible(False) # set visibility to false
59          self.options_layout.addWidget(self.bit_position_label)
60
61          self.bit_position_slider = QSlider(Qt.Orientation.Horizontal) # bit position slider
62          self.bit_position_slider.setRange(1, 8) # set range
63          self.bit_position_slider.setSingleStep(1) # set single step
64          self.bit_position_slider.setValue(8) #  set default value
65          self.bit_position_slider.setTickPosition(QSlider.TickPosition.TicksBelow) # set tick
            ↪  position
66          self.bit_position_slider.setTickInterval(1)
67          self.bit_position_slider.setVisible(False)
68          self.bit_position_slider.valueChanged.connect(self._update_json_display) # update json
            ↪  display on change
69          self.options_layout.addWidget(self.bit_position_slider)
70
71          bit_position_labels_layout = QHBoxLayout() # horizontal layout for bit position
            ↪  labels
72          self.least_significant_label = QLabel("Least Significant")
73          self.least_significant_label.setVisible(False)
74          bit_position_labels_layout.addWidget(self.least_significant_label)
75
76          bit_position_labels_layout.addStretch()
77
78          self.most_significant_label = QLabel("Most Significant")
79          self.most_significant_label.setVisible(False)
80          bit_position_labels_layout.addWidget(self.most_significant_label)
81
82          self.options_layout.addLayout(bit_position_labels_layout)
83
84          self.algorithm_dropdown.setCurrentText("X Significant Bit")
85          self._toggle_bit_position_fields("X Significant Bit")
86
```

```
87          self.noise_level_label = QLabel("Noise Level:")
88          self.options_layout.addWidget(self.noise_level_label)
89
90          self.noise_level_slider = QSlider(Qt.Orientation.Horizontal)
91          self.noise_level_slider.setRange(10, 100) # set range, actual value is divided by 10
92          self.noise_level_slider.setSingleStep(1) # set single step
93          self.noise_level_slider.setValue(10) # set default value
94          self.noise_level_slider.setTickPosition(QSlider.TickPosition.TicksBelow)
95          self.noise_level_slider.setTickInterval(10)
96          self.noise_level_slider.valueChanged.connect(self._update_noise_level_label)
97          self.noise_level_slider.valueChanged.connect(self._update_json_display)
98          self.options_layout.addWidget(self.noise_level_slider)
99
100         self.noise_level_value_label = QLabel("1.0") # noise level value label
101         self.options_layout.addWidget(self.noise_level_value_label)
102
103         self.save_config_button = QPushButton("Save Config")
104         self.save_config_button.setToolTip("Save the current configuration.")
105         self.save_config_button.clicked.connect(self._save_config)
106         self.options_layout.addWidget(self.save_config_button)
107
108         self.load_config_button = QPushButton("Load Config")
109         self.load_config_button.setToolTip("Load a custom configuration.")
110         self.load_config_button.clicked.connect(self._load_config)
111         self.options_layout.addWidget(self.load_config_button)
112
113         self.json_display = QTextEdit()
114         self.json_display.setReadOnly(True)
115         self.json_layout.addWidget(self.json_display)
116
117         self.copy_button = QPushButton("Copy JSON")
118         self.copy_button.setToolTip("Copy the JSON configuration to clipboard.")
119         self.copy_button.clicked.connect(self._copy_json_to_clipboard)
120         self.json_layout.addWidget(self.copy_button)
121
122         layout.addLayout(self.options_layout)
123         layout.addLayout(self.json_layout)
124
125         self._update_json_display()
126
127     def _toggle_aes_fields(self, encryption_type):
128         is_aes = encryption_type == "AES"
129         self.aes_key_label.setVisible(is_aes) # set visibility to is_aes (if encryption type
            ↪  is AES show key label)
130         self.aes_key_input.setVisible(is_aes)
131         self.aes_iv_label.setVisible(is_aes)
132         self.aes_iv_input.setVisible(is_aes)
133
134     def _toggle_bit_position_fields(self, algorithm_type):
135         is_xsb = algorithm_type == "X Significant Bit"
136         self.bit_position_label.setVisible(is_xsb) # set visibility to is_xsb (if algorithm
            ↪  type is XSB show bit position label)
137         self.bit_position_slider.setVisible(is_xsb)
138         self.least_significant_label.setVisible(is_xsb)
139         self.most_significant_label.setVisible(is_xsb)
140
141     def _update_noise_level_label(self, value):
```

```
142         self.noise_level_value_label.setText(f"{value / 10:.1f}") # set noise level value
            ↪ label
143
144     def _update_json_display(self):
145         # create config dictionary
146         config = {
147             "algorithm": self.algorithm_dropdown.currentText(),
148             "encryption": self.encryption_dropdown.currentText(),
149             "noise_level": self.noise_level_slider.value() / 10
150         }
151         if self.encryption_dropdown.currentText() == "AES": # addd key and iv if AES
152             config["key"] = self.aes_key_input.text()
153             config["iv"] = self.aes_iv_input.text()
154         if self.algorithm_dropdown.currentText() == "X Significant Bit": # add bit position if
            ↪ XSB
155             config["bit_position"] = self.bit_position_slider.value()
156         self.json_display.setText(json.dumps(config, indent=4))
157
158     def _pad_string(self, text, target_length=16):
159         # pad string to target length
160         if not text:
161             return ""
162         return (text * ((target_length // len(text)) + 1))[:target_length]
163
164     def _save_config(self):
165         # save config to file
166         self._update_json_display()
167         config = json.loads(self.json_display.toPlainText())
168
169         if config["encryption"] == "AES":
170             key = config.get("key", "")
171             iv = config.get("iv", "")
172
173             key_modified = False
174             iv_modified = False
175
176             if not key:
177                 key = os.urandom(16).hex()[:16]
178                 key_modified = True
179             elif len(key) != 16:
180                 key = self._pad_string(key)
181                 key_modified = True
182
183             if not iv:
184                 iv = os.urandom(16).hex()[:16]
185                 iv_modified = True
186             elif len(iv) != 16:
187                 iv = self._pad_string(iv)
188                 iv_modified = True
189
190             if key_modified or iv_modified:
191                 message = []
192                 if key_modified:
193                     message.append("Key was adjusted to 16 characters")
194                     self.aes_key_input.setText(key)
195                 if iv_modified:
196                     message.append("IV was adjusted to 16 characters")
197                     self.aes_iv_input.setText(iv)
```

```
198
199                 QMessageBox.information(
200                     self,
201                     "AES Parameters Adjusted",
202                     "\n".join(message)
203                 )
204
205             config["key"] = key
206             config["iv"] = iv
207             self._update_json_display()
208
209         file_name, _ = QFileDialog.getSaveFileName(self, "Save Config", "", "JSON Files
        ↪ (*.json);;All Files (*)")
210         if file_name:
211             with open(file_name, 'w') as file:
212                 json.dump(config, file)
213
214     def _load_config(self):
215         try:
216             file_dialog = QFileDialog()
217             file_path, _ = file_dialog.getOpenFileName(self, "Select Config File", "", "JSON
            ↪ Files (*.json);;All Files (*)")
218             if file_path:
219                 with open(file_path, 'r') as file:
220                     config = json.load(file)
221                     if self._validate_config(config): # validate config
222                         self.algorithm_dropdown.setCurrentText(config.get("algorithm", "Pixel
                        ↪ Value Differencing")) # set values
223                         self.encryption_dropdown.setCurrentText(config.get("encryption",
                        ↪ "None"))
224                         self.noise_level_slider.setValue(int(config.get("noise_level", 1.0) *
                        ↪ 10))
225                         if config.get("encryption") == "AES":
226                             self.aes_key_input.setText(config.get("key", "")) # set key and
                            ↪ iv
227                             self.aes_iv_input.setText(config.get("iv", ""))
228                         else:
229                             self.aes_key_input.clear() # clear key and iv
230                             self.aes_iv_input.clear()
231                         if config.get("algorithm") == "X Significant Bit":
232                             self.bit_position_slider.setValue(config.get("bit_position", 8)) #
                            ↪ set bit position
233                         self._update_json_display() # update json display with loaded config
234                     else:
235                         self._show_error_message("Invalid configuration file.")
236         except Exception as e:
237             self._show_error_message(f"Error loading config: {e}.\nMake sure the file is a
            ↪ valid JSON file.")
238
239     def _validate_config(self, config):
240         # config requirements
241         required_keys = ["algorithm", "encryption", "noise_level"]
242         valid_algorithms = ["X Significant Bit", "Pixel Value Differencing"]
243         valid_encryptions = ["None", "Base64", "AES"]
244
245         for key in required_keys:
246             if key not in config:
247                 return False
```

```
248         if config["algorithm"] not in valid_algorithms:
249             return False
250         if config["encryption"] not in valid_encryptions:
251             return False
252         if config["encryption"] == "AES" and ("key" not in config or "iv" not in config):
253             return False
254         if config["algorithm"] == "X Significant Bit" and "bit_position" not in config:
255             return False
256         return True # all config checks passed
257 
258     def _copy_json_to_clipboard(self):
259         pyperclip.copy(self.json_display.toPlainText()) # copy json to clipboard
260 
261     def _show_error_message(self, message):
262         error_dialog = QMessageBox()
263         error_dialog.setIcon(QMessageBox.Icon.Critical)
264         error_dialog.setText(message)
265         error_dialog.setWindowTitle("Error")
266         error_dialog.exec()
```

6.1.2.5 conversion_page.py

Code from `conversion_page.py`:

```
1  from PyQt6.QtWidgets import QWidget, QVBoxLayout, QLabel, QLineEdit, QPushButton, QComboBox,
   ↪  QProgressBar, QFileDialog, QCheckBox, QSpinBox
2  from PIL import Image
3  import os
4  from data_structures.linkedlist import LinkedList
5  
6  class ConversionPage(QWidget):
7      def __init__(self):
8          super().__init__()
9          self._init_ui()
10         self._task_list = LinkedList()
11 
12     def _init_ui(self):
13         layout = QVBoxLayout(self)
14 
15         self._convert_label = QLabel("Select image(s) to convert:")  # image selection label
16         layout.addWidget(self._convert_label) # add label to layout
17 
18         self._convert_path = QLineEdit()  # image path input field
19         self._convert_path.setToolTip("Path to the image(s) to be converted.")
20         layout.addWidget(self._convert_path)
21 
22         self._convert_browse_button = QPushButton("Browse")  # browse for images button
23         self._convert_browse_button.setToolTip("Browse and select image(s) to convert.") #
           ↪  tooltip for browse button
24         self._convert_browse_button.clicked.connect(self._browse_images) # connect browse
           ↪  button to browse_images method
25         layout.addWidget(self._convert_browse_button)
26 
27         self._batch_convert_checkbox = QCheckBox("Convert all images in directory")  # batch
           ↪  conversion checkbox
28         self._batch_convert_checkbox.setToolTip("Check to convert all images in the selected
           ↪  directory.")
29         layout.addWidget(self._batch_convert_checkbox)
```

```
30
31          self._output_dir_label = QLabel("Select output directory:")
32          layout.addWidget(self._output_dir_label)
33
34          self._output_dir_path = QLineEdit()
35          self._output_dir_path.setToolTip("Path to the directory where converted images will be
            ↪  saved.")
36          layout.addWidget(self._output_dir_path)
37
38          self._output_dir_browse_button = QPushButton("Browse")
39          self._output_dir_browse_button.setToolTip("Browse and select the output directory.")
40          self._output_dir_browse_button.clicked.connect(self._browse_output_directory)
41          layout.addWidget(self._output_dir_browse_button)
42
43          self._extension_label = QLabel("Select output format:")
44          layout.addWidget(self._extension_label)
45
46          self._extension_dropdown = QComboBox()  # output format dropdown
47          self._extension_dropdown.addItems([".png", ".jpg", ".bmp"]) # add items to dropdown
48          self._extension_dropdown.setToolTip("Select the output format for the converted
            ↪  images.")
49          self._extension_dropdown.currentIndexChanged.connect(self._toggle_quality_options) #
            ↪  connect to method to toggle quality options
50          layout.addWidget(self._extension_dropdown)
51
52          self._quality_label = QLabel("Set image quality (1-100):")
53          layout.addWidget(self._quality_label)
54
55          self._quality_spinbox = QSpinBox()  # image quality spinbox
56          self._quality_spinbox.setRange(1, 100) # spinbox range
57          self._quality_spinbox.setValue(90) # set default value
58          self._quality_spinbox.setToolTip("Set the quality of .jpg output images (1-100).")
59          layout.addWidget(self._quality_spinbox)
60
61          self._overwrite_checkbox = QCheckBox("Overwrite existing files")
62          self._overwrite_checkbox.setToolTip("Check to overwrite existing files in the output
            ↪  directory.")
63          layout.addWidget(self._overwrite_checkbox)
64
65          self._resize_checkbox = QCheckBox("Resize images")
66          self._resize_checkbox.setToolTip("Check to resize the images during conversion.")
67          self._resize_checkbox.stateChanged.connect(self._toggle_resize_options)
68          layout.addWidget(self._resize_checkbox)
69
70          self._resize_width_label = QLabel("Width:")
71          self._resize_width_label.setEnabled(False) # disable width label by default
72          layout.addWidget(self._resize_width_label)
73
74          self._resize_width_spinbox = QSpinBox()
75          self._resize_width_spinbox.setRange(1, 10000)
76          self._resize_width_spinbox.setEnabled(False) # disable width spinbox by default
77          self._resize_width_spinbox.setToolTip("Set the width for resizing the images.")
78          layout.addWidget(self._resize_width_spinbox)
79
80          self._resize_height_label = QLabel("Height:")
81          self._resize_height_label.setEnabled(False)
82          layout.addWidget(self._resize_height_label)
83
```

```
84          self._resize_height_spinbox = QSpinBox()
85          self._resize_height_spinbox.setRange(1, 10000)
86          self._resize_height_spinbox.setEnabled(False)
87          self._resize_height_spinbox.setToolTip("Set the height for resizing the images.")
88          layout.addWidget(self._resize_height_spinbox)
89
90          self._maintain_aspect_ratio_checkbox = QCheckBox("Maintain aspect ratio")
91          self._maintain_aspect_ratio_checkbox.setEnabled(False)
92          self._maintain_aspect_ratio_checkbox.setToolTip("Check to maintain the aspect ratio
            ↪  when resizing images.")
93          layout.addWidget(self._maintain_aspect_ratio_checkbox)
94
95          self._convert_button = QPushButton("Convert")
96          self._convert_button.setToolTip("Start the conversion process.")
97          self._convert_button.clicked.connect(self._convert_images)
98          layout.addWidget(self._convert_button)
99
100         self._progress_bar = QProgressBar()  # conversion progress bar
101         layout.addWidget(self._progress_bar)
102
103         self._status_label = QLabel("Status: Ready")
104         layout.addWidget(self._status_label)
105
106         self._toggle_quality_options()  # initial call to set visibility based on default
            ↪  selection
107
108     def _browse_images(self):
109         if self._batch_convert_checkbox.isChecked():
110             dir_dialog = QFileDialog() # directory dialog
111             directory = dir_dialog.getExistingDirectory(self, "Select Directory")
112             if directory:
113                 self._convert_path.setText(directory) # set directory path in input field
114         else:
115             file_dialog = QFileDialog() # file dialog
116             file_paths, _ = file_dialog.getOpenFileNames(self, "Select Images", "", "Images
                ↪  (*.png *.jpg *.bmp)") # get file paths
117             if file_paths:
118                 self._convert_path.setText("; ".join(file_paths)) # set file paths in input
                    ↪  field, joined by "; " in order to separate multiple paths
119
120     def _browse_output_directory(self):
121         dir_dialog = QFileDialog()
122         output_dir = dir_dialog.getExistingDirectory(self, "Select Output Directory")
123         if output_dir:
124             self._output_dir_path.setText(output_dir) # set output directory path in input
                ↪  field if it exists
125
126     def _toggle_resize_options(self): # method to enable/disable resize options based on
        ↪  checkbox state
127         enabled = self._resize_checkbox.isChecked()
128         self._resize_width_label.setEnabled(enabled)
129         self._resize_width_spinbox.setEnabled(enabled)
130         self._resize_height_label.setEnabled(enabled)
131         self._resize_height_spinbox.setEnabled(enabled)
132         self._maintain_aspect_ratio_checkbox.setEnabled(enabled)
133
134     def _toggle_quality_options(self): # method to show/hide quality options based on output
        ↪  format
```

```
135         is_jpg = self._extension_dropdown.currentText() == ".jpg"
136         self._quality_label.setVisible(is_jpg)
137         self._quality_spinbox.setVisible(is_jpg)
138 
139     def _convert_images(self): # method to convert images
140         try:
141             file_paths = self._get_file_paths()
142         except (FileNotFoundError, NotADirectoryError) as e:
143             self._status_label.setText(str(e))
144             return
145         output_dir = self._output_dir_path.text()
146         if not os.path.isdir(output_dir):
147             self._status_label.setText(f"The output directory does not exist: '{output_dir}'")
148             return
149         file_paths = self._merge_sort(file_paths)  # sort file paths using Mergesort
150         output_format = self._extension_dropdown.currentText()
151         quality = self._quality_spinbox.value()
152         overwrite = self._overwrite_checkbox.isChecked()
153         resize = self._resize_checkbox.isChecked()
154         maintain_aspect_ratio = self._maintain_aspect_ratio_checkbox.isChecked()
155         width = self._resize_width_spinbox.value()
156         height = self._resize_height_spinbox.value()
157         total_files = len(file_paths) # total number of files to convert
158 
159         # Add tasks to the linked list
160         for file_path in file_paths:
161             self._task_list.append((file_path, output_format, output_dir, quality, overwrite,
                ↪  resize, maintain_aspect_ratio, width, height))
162 
163         # Process tasks from the linked list
164         while not self._task_list.is_empty():
165             task = self._task_list.pop()
166             try:
167                 self._process_image(*task)
168             except Exception as e:
169                 self._status_label.setText(f"Error converting {task[0]}: {e}")
170                 return
171 
172             self._progress_bar.setValue(int((total_files - self._task_list_length()) /
                ↪  total_files * 100)) # update progress bar
173             self._status_label.setText(f"Converting {total_files -
                ↪  self._task_list_length()}/{total_files} images...") # update status label
174 
175         self._status_label.setText("Conversion complete!")
176 
177     def _task_list_length(self):
178         return self._task_list.length()
179 
180     def _get_file_paths(self):
181         path = self._convert_path.text()
182         if not path:
183             raise ValueError("No file or directory selected")
184 
185         if self._batch_convert_checkbox.isChecked():
186             # handle batch conversion from directory
187             if os.path.isfile(path):
188                 path = os.path.dirname(path)  # convert file path to directory path
189             if not os.path.isdir(path):
```

```
                raise NotADirectoryError(f"The directory does not exist: '{path}'")
            return [os.path.join(path, file_name)
                    for file_name in os.listdir(path)
                    if file_name.lower().endswith(('.png', '.jpg', '.bmp'))]
        else:
            # handle single or multiple file selection
            file_paths = [p.strip() for p in path.split(";") if p.strip()]
            for file_path in file_paths:
                if not os.path.isfile(file_path):
                    raise FileNotFoundError(f"The file does not exist: '{file_path}'")
            return file_paths

    def _process_image(self, file_path, output_format, output_dir, quality, overwrite, resize,
    ↪ maintain_aspect_ratio, width, height):
        img = Image.open(file_path)
        if resize:
            img = self._resize_image(img, maintain_aspect_ratio, width, height) # resize
            ↪ image
        if output_format == ".jpg" and img.mode == "RGBA": # convert RGBA to RGB for .jpg
        ↪ format
            img = img.convert("RGB") # convert img to RGB mode
        output_path = self._get_output_path(file_path, output_format, output_dir, overwrite)
        try:
            with open(output_path, 'wb') as f:  # ensure the file can be opened for writing
                if output_format == ".jpg":
                    img.save(f, format="JPEG", quality=quality) # save with specified quality
                    ↪ for JPEG
                else:
                    img.save(f, format=output_format[1:].upper()) # save without quality for
                    ↪ other formats
        except Exception as e:
            self._status_label.setText(f"Error saving {output_path}: {e}")
            raise

    def _resize_image(self, img, maintain_aspect_ratio, width, height):
        if maintain_aspect_ratio:
            img.thumbnail((width, height)) # resize  while maintaining aspect ratio
        else:
            img = img.resize((width, height)) # resize without maintaining aspect ratio
        return img

    def _get_output_path(self, file_path, output_format, output_dir, overwrite):
        output_path = os.path.join(output_dir, os.path.basename(file_path).rsplit('.', 1)[0] +
        ↪ output_format) # create output path
        if not output_path:
            raise ValueError("Output directory is invalid")
        if not overwrite and os.path.exists(output_path):
            base, ext = os.path.splitext(output_path) # split path into base and extension
            counter = 1
            while os.path.exists(output_path):
                output_path = f"{base}_{counter}{ext}" # add counter to filename if file
                ↪ already exists
                counter += 1
        return output_path

    def _merge_sort(self, file_paths):
        if len(file_paths) <= 1:
            return file_paths
```

```
241         mid = len(file_paths) // 2 # find middle index
242         left_half = self._merge_sort(file_paths[:mid]) # recursively sort left half
243         right_half = self._merge_sort(file_paths[mid:]) # recursively sort right half
244         return self._merge(left_half, right_half)
245 
246     def _merge(self, left, right):
247         sorted_list = []
248         while left and right:
249             if left[0] <= right[0]: # compare first elements of left and right lists
250                 sorted_list.append(left.pop(0)) # remove first element from left list and
                    ↪ append to sorted list
251             else:
252                 sorted_list.append(right.pop(0))
253         sorted_list.extend(left or right) # extend sorted list with remaining elements from
            ↪ left or right list
254         return sorted_list
```

6.1.3 enc

6.1.3.1 aes.py

Code from `aes.py`:

```
1  class AESUtils:
2      @staticmethod
3      def _multiply_time(byte_val):
4          return (((byte_val << 1) ^ 0x1B) & 0xFF) if (byte_val & 0x80) else (byte_val << 1) #
           ↪ returns mult of byte by 2 if less than 0x80, else returns multiplication of byte
           ↪ by 2 and xors result with 0x1B
5  
6      @staticmethod
7      def _convert_bytes_to_matrix(data_bytes):
8          return [list(data_bytes[i:i+4]) for i in range(0, len(data_bytes), 4)] # returns list
           ↪ of lists, 4 bytes each
9  
10     @staticmethod
11     def _convert_matrix_to_bytes(matrix_data):
12         return bytes(sum(matrix_data, [])) # returns bytes object of matrix data
13 
14     @staticmethod
15     def _xor_two_bytes(a_bytes, b_bytes):
16         return bytes(a ^ b for a, b in zip(a_bytes, b_bytes)) # returns bytes object of xor of
           ↪ two bytes objects
17 
18     @staticmethod
19     def _apply_padding(text):
20         pad_length = 16 - (len(text) % 16) # calculates padding length
21         padding = bytes([pad_length] * pad_length) # creates bytes object of padding length
22         return text + padding
23 
24     @staticmethod
25     def _remove_padding(text):
26         pad_len = text[-1] # gets last byte of text
27         return text[:-pad_len] # returns text without padding
28 
29     @staticmethod
30     def _divide_into_blocks(message, size=16):
31         return [message[i:i+size] for i in range(0, len(message), size)] # returns list of
           ↪ blocks of size 16
```

```
32
33      @staticmethod
34      def _multiply_poly(a, b):
35          result = 0
36          while a: # while a =! 0
37              if a & 1:
38                  result ^= b # xor result with b if a is odd
39              a >>= 1 # right shift a
40              b <<= 1 # left shift b
41          return result
42
43      @staticmethod
44      def _modulo_polynomial(n, mod):
45          while (n.bit_length()) >= (mod.bit_length()): # while n greater than or equal to mod
            ↪  in bit length
46              shift = n.bit_length() - mod.bit_length()
47              n ^= mod << shift # xor n with mod left shifted by shift
48          return n
49
50      @staticmethod
51      def _galois_mult(a, b):
52          product = AESUtils._multiply_poly(a, b)
53          modulus = 0x11b # x^8 + x^4 + x^3 + x + 1 // 100011011
54          return AESUtils._modulo_polynomial(product, modulus)
55
56      @staticmethod
57      def _galois_inverse(a): # calculates inverse of a in galois field (used for affine
        ↪  transformation)
58          if a == 0:
59              return 0
60          for i in range(1, 256):
61              if AESUtils._galois_mult(a, i) == 1:
62                  return i
63
64      @staticmethod
65      def _bitwise_dot(a, b):
66          product = a & b # bitwise and of a and b
67          result = 0
68          while product:
69              result ^= product & 1 # xor result with last bit of product
70              product >>= 1 # right shift product
71          return result
72
73      @staticmethod
74      def _affine_trans(matrix, vector, const):
75          result = 0
76          for i in range(8):
77              row = (matrix >> (8 * i)) & 0xff # get ith row of matrix
78              bit = AESUtils._bitwise_dot(row, vector) # calculate dot product of ith row and
                ↪  vector
79              result |= (bit << i) # set ith bit of result to bit
80          return result ^ const # xor result with const
81
82      @staticmethod
83      def _compute_sbox(val):
84          inv = AESUtils._galois_inverse(val)
85          trans_matrix = int('F87C3E1F8FC7E3F1', 16) # standard rijndael affine transformation
            ↪  matrix, hex
```

```
86          const = int('63', 16) # standard rijndael affine transformation constant, hex
87          return AESUtils._affine_trans(trans_matrix, inv, const)
88
89      @staticmethod
90      def _generate_sbox(): # actual sbox generation
91          sbox = [AESUtils._compute_sbox(i) for i in range(256)]
92          return tuple(sbox)
93
94      @staticmethod
95      def _create_round_constants():
96          constants = [0x00, 0x01] # key expansion constants
97          for _ in range(2, 256):
98              constants.append(AESUtils._multiply_time(constants[-1])) # appends multiplication
                ↪  of last element of constants with 0x02
99          return tuple(constants)
100
101     @staticmethod
102     def _shift_row(matrix):
103         for i in range(1, 4):
104             matrix[i] = matrix[i][i:] + matrix[i][:i] # shifts ith row of matrix by i
105
106     @staticmethod
107     def _inverse_shift_row(matrix):
108         for i in range(1, 4):
109             matrix[i] = matrix[i][-i:] + matrix[i][:-i] # shifts ith row of matrix by -i
110
111     @staticmethod
112     def _mix_columns(state):
113         for i in range(4): # for each column
114             column = state[i]
115             temp = column[0] ^ column[1] ^ column[2] ^ column[3] # xor of all elements of
                ↪  column
116             original = column[0]
117             column[0] ^= temp ^ AESUtils._multiply_time(column[0] ^ column[1]) # xor of temp
                ↪  and multiplication of first and second element of column
118             column[1] ^= temp ^ AESUtils._multiply_time(column[1] ^ column[2])
119             column[2] ^= temp ^ AESUtils._multiply_time(column[2] ^ column[3])
120             column[3] ^= temp ^ AESUtils._multiply_time(column[3] ^ original)
121
122     @staticmethod
123     def _inverse_mix_columns(state):
124         for i in range(4):
125             u = AESUtils._multiply_time(AESUtils._multiply_time(state[i][0] ^ state[i][2])) #
                ↪  multiplication of first and third element of column
126             v = AESUtils._multiply_time(AESUtils._multiply_time(state[i][1] ^ state[i][3]))
127             for j in range(4):
128                 state[i][j] ^= u if j % 2 == 0 else v # xor of u if j is even, else xor of v
129         AESUtils._mix_columns(state)
130
131     @staticmethod
132     def _increment_bytes(a): # increments bytes by 1 - key expansion
133         out = list(a) # converts a to list
134         for i in reversed(range(len(out))): # for each element in out
135             if out[i] != 0xFF: # if element not 0xFF (stops overflow since 0xFF + 1 = 0)
136                 out[i] += 1
137                 break
138             out[i] = 0
139         return bytes(out)
```

```
140
141     @staticmethod
142     def _substitute_bytes(state, sbox):
143         for i in range(4):
144             state[i] = [sbox[b] for b in state[i]] # substitutes each byte in state with sbox
                ↪  value
145
146     @staticmethod
147     def _inverse_substitute_bytes(state, inv_sbox):
148         for i in range(4):
149             state[i] = [inv_sbox[b] for b in state[i]] # sub in state with inv sbox
150
151     @staticmethod
152     def _add_round_key_func(state, key):
153         for i in range(4):
154             state[i] = [state[i][j] ^ key[i][j] for j in range(4)] # xor of state and key
155
156 class AESAlgorithm:
157     def __init__(self, key):
158         self._num_rounds = 16
159         self._sbox = AESUtils._generate_sbox()
160         self._inv_sbox = tuple(self._sbox.index(i) for i in range(256))
161         self._constants = AESUtils._create_round_constants()
162         self._key_matrices = self._expand_key(key)
163
164     def _expand_key(self, key):
165         key_cols = AESUtils._convert_bytes_to_matrix(key)
166         iter_size = len(key) // 4 # size of each iteration
167         i = 1 # round constant index
168
169         while len(key_cols) < (self._num_rounds + 1) * 4: # while key_cols is less than 4 *
            ↪  number of rounds + 1
170             word = key_cols[-1][:] # last element of key_cols
171             if len(key_cols) % iter_size == 0:
172                 word = [self._sbox[b] for b in word[1:] + word[:1]] # substitute bytes
173                 word[0] ^= self._constants[i]
174                 i += 1
175             elif len(key) == 32 and len(key_cols) % iter_size == 4: # if key length is 32 and
                ↪  len of key_cols is multiple of 4
176                 word = [self._sbox[b] for b in word]
177             word = AESUtils._xor_two_bytes(word, key_cols[-iter_size]) # xor of word and last
                ↪  element of key_cols
178             key_cols.append(word)
179
180         return [key_cols[j:j + 4] for j in range(0, len(key_cols), 4)] # returns key_cols
            ↪  divided into blocks of 4
181
182     def _process_block(self, block, encrypt=True):
183         state = AESUtils._convert_bytes_to_matrix(block)
184         if encrypt: # if encrypting, does all steps of aes
185             AESUtils._add_round_key_func(state, self._key_matrices[0])
186             for rnd in range(1, self._num_rounds):
187                 AESUtils._substitute_bytes(state, self._sbox)
188                 AESUtils._shift_row(state)
189                 AESUtils._mix_columns(state)
190                 AESUtils._add_round_key_func(state, self._key_matrices[rnd])
191             AESUtils._substitute_bytes(state, self._sbox)
192             AESUtils._shift_row(state)
```

```
193             AESUtils._add_round_key_func(state, self._key_matrices[-1])
194         else: # if decrypting, does all steps of aes in reverse
195             AESUtils._add_round_key_func(state, self._key_matrices[-1])
196             AESUtils._inverse_shift_row(state)
197             AESUtils._inverse_substitute_bytes(state, self._inv_sbox)
198             for rnd in range(self._num_rounds - 1, 0, -1): # starts from last round and goes
                ↪  to first
199                 AESUtils._add_round_key_func(state, self._key_matrices[rnd])
200                 AESUtils._inverse_mix_columns(state)
201                 AESUtils._inverse_shift_row(state)
202                 AESUtils._inverse_substitute_bytes(state, self._inv_sbox)
203             AESUtils._add_round_key_func(state, self._key_matrices[0])
204         return AESUtils._convert_matrix_to_bytes(state)
205 
206     def encrypt_block(self, plaintext): # encrypts block, requires block of 16 bytes
207         assert len(plaintext) == 16
208         return self._process_block(plaintext, True)
209 
210     def decrypt_block(self, ciphertext): # decrypts block
211         assert len(ciphertext) == 16
212         return self._process_block(ciphertext, False)
213 
214     def encrypt_cbc_mode(self, plaintext, iv):
215         assert len(iv) == 16
216         padded = AESUtils._apply_padding(plaintext) # pads plaintext in order to make it
            ↪  multiple of 16
217         previous = iv
218         blocks = [self.encrypt_block(AESUtils._xor_two_bytes(block, previous)) for block in
            ↪  AESUtils._divide_into_blocks(padded)] # encrypts each block of plaintext
219         encrypted_data = b''.join(blocks) # returns joined blocks
220         return encrypted_data
221 
222     def decrypt_cbc_mode(self, ciphertext, iv):
223         assert len(iv) == 16
224         previous = iv
225         blocks = [AESUtils._xor_two_bytes(previous, self.decrypt_block(block)) for block in
            ↪  AESUtils._divide_into_blocks(ciphertext)] # decrypts each block of ciphertext
226         decrypted_data = AESUtils._remove_padding(b''.join(blocks)) # removes padding and
            ↪  returns joined blocks
227         return decrypted_data
228 
229 
230 def aes_test():
231     aes = AESAlgorithm(b"testkey123456789")
232     iv = b"testiv1234567890"
233     plain_text = "The quick brown fox jumps over the lazy dog!!@~$$%^&*()_+"
234     cipher = aes.encrypt_cbc_mode(plain_text.encode(), iv)
235     decrypted = aes.decrypt_cbc_mode(cipher, iv).decode()
236     print("Encrypted:", cipher)
237     print("Decrypted:", decrypted)
238 
239 if __name__ == "__main__":
240     aes_test()
```

6.1.3.2 noise.py

Code from `noise.py`:

```python
import random
from PIL import Image

class Noise:
    @staticmethod
    def add_noise(image, noise_level, data_length):
        new_image = image.copy() # copy image and get width, height, and pixel data
        width, height = new_image.size
        pixels = new_image.load()

        noise_level_int = int(noise_level * 1000)  # convert to int, *1000 to ensure not a float
        skip_pixels = data_length * 8 * 3  # calc no. pixels to skip based on data length (*8 for bits, *3 for rgb)

        for _ in range(noise_level_int):
            x, y = random.randint(0, width - 1), random.randint(0, height - 1) # generate random pixel coordinates
            pixel_index = y * width + x # pixel index used to skip pixels
            if pixel_index < skip_pixels: # skip pixels containing embedded data
                continue
            r, g, b = pixels[x, y] # get pixel's rgb
            noise = random.randint(-int(noise_level), int(noise_level))  # generate random noise
            pixels[x, y] = (Noise._clamp(r + noise), Noise._clamp(g + noise), Noise._clamp(b + noise))  # actually add noise

        return new_image

    @staticmethod
    def _clamp(value):
        return max(0, min(255, value))  # ensure value is within range [0, 255] (inclusive) (rgb)
```

6.1.4 meth

6.1.4.1 xsb.py

Code from `xsb.py`:

```python
class SignificantBit:
    @staticmethod
    def _transform_data_to_binary(data):
        return [format(byte, '08b') for byte in data] # convert data to binary

    @staticmethod
    def _manipulate_pixels(pixels, data, bit_position):
        bit_position = min(7, max(0, bit_position)) # ensure bit_position is within valid range (0-7)
        binary_data = SignificantBit._transform_data_to_binary(data) # convert data to binary
        data_length = len(binary_data)
        pixel_iterator = iter(pixels)
        for idx in range(data_length): # iterate over data
            pixel_block = []
            for _ in range(3):
                pixel_block.extend(next(pixel_iterator)[:3]) # collect 9 pixel values (3 RGB pixels)
            for bit_idx in range(8): # iterate over bits in byte
```

```
17                  bit_mask = (1 << bit_position)
18                  if binary_data[idx][bit_idx] == '0': # check if bit is 0
19                      pixel_block[bit_idx] = pixel_block[bit_idx] & ~bit_mask # clear the
                        ↪ specified bit
20                  else:
21                      pixel_block[bit_idx] = pixel_block[bit_idx] | bit_mask # set the specified
                        ↪ bit
22              if idx == data_length - 1:
23                  pixel_block[8] = pixel_block[8] & ~(1 << bit_position) # end of data marker -
                    ↪ clear the bit
24              else:
25                  pixel_block[8] = pixel_block[8] | (1 << bit_position) # more data follows - set
                    ↪ the bit
26              yield tuple(pixel_block[0:3]) # return the pixel groups
27              yield tuple(pixel_block[3:6])
28              yield tuple(pixel_block[6:9])
29
30      @staticmethod
31      def embed(image, data, bit_depth=8, bit_position=0): # embed data in image at specified
        ↪ bit position
32          if not data:
33              raise ValueError('Data is empty')
34          bit_position = min(7, max(0, bit_position)) # ensure bit_position is within valid
            ↪ range (0-7)
35          new_image = image.copy()
36          width = new_image.size[0]
37          x, y = 0, 0
38          for pixel in SignificantBit._manipulate_pixels(new_image.getdata(), data,
            ↪ bit_position): # iterate over pixels and modify them
39              new_image.putpixel((x, y), pixel) # set the pixel value
40              x += 1
41              if x >= width:
42                  x = 0 # reset x if at end of row
43                  y += 1
44          return new_image
45
46      @staticmethod
47      def extract(image, bit_depth=8, bit_position=0): # extract data from image at specified
        ↪ bit position
48          bit_position = min(7, max(0, bit_position)) # ensure bit_position is within valid
            ↪ range (0-7)
49          extracted_data = ''
50          pixel_iterator = iter(image.getdata())
51          bit_mask = 1 << bit_position # create bit mask (used to extract specific bit)
52          char_counter = 0
53          try:
54              while True:
55                  pixels_block = []
56                  try:
57                      for _ in range(3): # iterate over 3 pixels
58                          pixel = next(pixel_iterator) # get the pixel value
59                          pixels_block.extend(pixel[:3]) # collect 9 pixel values
60                  except StopIteration:
61                      break
62                  binary_string = ''
63                  for i in range(8): # iterate over bits in byte
64                      bit_value = '0' if (pixels_block[i] & bit_mask) == 0 else '1'
65                      binary_string += bit_value # extract bits from first 8 pixels
```

```
                try:
                    int_value = int(binary_string, 2) # convert binary to integer
                    char = chr(int_value) # convert binary to character
                    extracted_data += char # add character to extracted data
                    char_counter += 1
                except ValueError:
                    break
                end_marker_bit = (pixels_block[8] & bit_mask) == 0 # check if this is the end
                ↪  of data
                if end_marker_bit:
                    break
                if char_counter > 10000: # safety check to prevent infinite loops
                    break
        except Exception: # shouldn't happen, but just in case
            pass

        return extracted_data # return the extracted data
```

6.1.4.2 pvd.py

Code from `pvd.py`:

```
from PIL import Image
import numpy as np

class PVDAlgorithm:
    # range table defines pixel difference ranges and bits that can be stored:
    # smaller differences (smooth areas) store fewer bits to maintain image quality
    # larger differences (edge areas) can store more bits as changes are less noticeable
    RANGE_TABLE = (
        (0, 7),     # smooth regions: 3 bits - minimal visual impact
        (8, 15),    # slight texture: 3 bits - still maintains quality
        (16, 31),   # more texture: 4 bits - moderate capacity
        (32, 63),   # edges start: 5 bits - higher capacity
        (64, 127),  # strong edges: 6 bits - even more data
        (128, 255) # dramatic changes: 7 bits - maximum capacity
    )
    BITS_PER_RANGE = (3, 3, 4, 5, 6, 7) # lookup table for quick bit capacity checks

    @staticmethod
    def _get_range_index(diff): # optimized range lookup - avoids binary search
        if diff <= 7: return 0
        elif diff <= 15: return 1
        elif diff <= 31: return 2
        elif diff <= 63: return 3
        elif diff <= 127: return 4
        return 5

    @staticmethod
    def embed(image, data): # embed data using PVD - modifies pixel pairs based on their
    ↪  difference
        if not data:
            raise ValueError('Data is empty')
        pixel_array = np.array(image) # convert to numpy array for faster operations
        binary_data = ''.join(format(byte, '08b') for byte in data + b'###END###') # add end
        ↪  marker for extraction
        height, width = pixel_array.shape[:2]
        data_index = 0 # tracks position in binary data string
```

```
35          data_len = len(binary_data)
36
37          for y in range(height):
38              if data_index >= data_len: # all data embedded
39                  break
40              for x in range(0, width - 1, 2): # process pixel pairs (p1,p2) in each row
41                  if data_index >= data_len:
42                      break
43                  for c in range(3): # embed in each RGB channel
44                      if data_index >= data_len:
45                          break
46                      # get pixel pair values and calculate their difference
47                      p1 = int(pixel_array[y, x, c])
48                      p2 = int(pixel_array[y, x + 1, c])
49                      diff = abs(p2 - p1) # original difference determines embedding capacity
50
51                      # determine how many bits we can embed based on the difference
52                      range_idx = PVDAlgorithm._get_range_index(diff)
53                      num_bits = PVDAlgorithm.BITS_PER_RANGE[range_idx] # get capacity for this
                        ↪  range
54                      lower = PVDAlgorithm.RANGE_TABLE[range_idx][0] # lower bound of range
55
56                      # extract bits to embed and calculate new difference to achieve
57                      to_embed = int(binary_data[data_index:data_index + num_bits], 2)
58                      new_diff = lower + to_embed # target difference after embedding
59
60                      # adjust pixel values to achieve new difference while minimizing changes
61                      if p1 <= p2: # maintain relative ordering of pixels
62                          if new_diff > diff: # need to increase difference
63                              p1_new = p1 # keep smaller pixel same
64                              p2_new = p1 + new_diff # adjust larger pixel up
65                          else: # need to decrease difference
66                              p2_new = p2 # keep larger pixel same
67                              p1_new = p2 - new_diff # adjust smaller pixel up
68                      else: # p1 > p2 case
69                          if new_diff > diff:
70                              p2_new = p2 # keep smaller pixel same
71                              p1_new = p2 + new_diff # adjust larger pixel up
72                          else:
73                              p1_new = p1 # keep larger pixel same
74                              p2_new = p1 - new_diff # adjust smaller pixel down
75
76                      # clamp values to valid pixel range (0-255)
77                      p1_new = max(0, min(255, p1_new))
78                      p2_new = max(0, min(255, p2_new))
79
80                      # update pixel values and move to next bits
81                      pixel_array[y, x, c] = p1_new
82                      pixel_array[y, x + 1, c] = p2_new
83                      data_index += num_bits
84          return Image.fromarray(pixel_array)
85
86      @staticmethod
87      def extract(image): # extract hidden data by reading pixel pair differences
88          pixel_array = np.array(image)
89          height, width = pixel_array.shape[:2]
90          bytes_data = bytearray() # stores extracted bytes
91          current_byte = 0 # builds up byte from extracted bits
```

```
        bit_count = 0 # tracks bits in current byte

        for y in range(height):
            for x in range(0, width - 1, 2): # process pixel pairs
                for c in range(3): # check each RGB channel
                    # get pixel pair and their difference
                    p1 = pixel_array[y, x, c]
                    p2 = pixel_array[y, x + 1, c]
                    diff = abs(int(p2) - int(p1))

                    # determine how many bits were embedded here
                    range_idx = PVDAlgorithm._get_range_index(diff)
                    num_bits = PVDAlgorithm.BITS_PER_RANGE[range_idx]
                    lower = PVDAlgorithm.RANGE_TABLE[range_idx][0]

                    # extract the embedded bits from the difference
                    embedded = diff - lower # remove range offset to get embedded value

                    for _ in range(num_bits): # extract bits one at a time
                        # shift bits left and add next bit from embedded value
                        current_byte = (current_byte << 1) | ((embedded >> (num_bits - 1)) & 1)
                        embedded <<= 1
                        bit_count += 1

                        if bit_count == 8: # completed a byte
                            bytes_data.append(current_byte)
                            current_byte = 0
                            bit_count = 0

                            # check for end marker once we have enough data
                            if len(bytes_data) >= 8:
                                try:
                                    text = bytes_data.decode('ascii')
                                    if '###END###' in text: # found end marker
                                        return text[:text.index('###END###')]
                                except UnicodeDecodeError:
                                    continue # keep going if we hit invalid ascii
        try:
            return bytes_data.decode('ascii') # attempt final decode of any remaining data
        except UnicodeDecodeError:
            return ''
```

6.2 PlantUML Appendix

6.2.0.1 main.uml

Code from `main.uml`:

```
@startuml
hide empty members

skinparam class {
    BackgroundColor White
    BorderColor Black
    ArrowColor Black
}

skinparam classAttribute {
```

```
    IconSize 12
    IconPrivate Red
    IconPublic SpringGreen
}


class Steganography {
    -__init__(config)
    -_initialize_encryption()
    +load_config(file_path)
    +embed_text(image_path, text)
    +save_image(image, save_path)
    +decode_text(image_path)
    -_extract_data(image)
    -_apply_algorithm(image, data)
    -_apply_encryption(data)
    -_apply_decryption(data)
}

class HashNode {
    -__init__(key, value)
}

class HashTable {
    -__init__(size)
    -_hash(key)
    +insert(key, value)
    +get(key, default)
    +remove(key)
    -__len__()
    -__contains__(key)
    +clear()
}

class ListNode {
    -__init__(data)
    +data()
    +next()
    +next(value)
}

class LinkedList {
    -__init__()
    +append(data)
    +pop()
    +is_empty()
    +length()
}

class AESUtils {
    -_multiply_time(byte_val)
    -_convert_bytes_to_matrix(data_bytes)
    -_convert_matrix_to_bytes(matrix_data)
    -_xor_two_bytes(a_bytes, b_bytes)
    -_apply_padding(text)
    -_remove_padding(text)
    -_divide_into_blocks(message, size)
    -_multiply_poly(a, b)
```

```
    -_modulo_polynomial(n, mod)
    -_galois_mult(a, b)
    -_galois_inverse(a)
    -_bitwise_dot(a, b)
    -_affine_trans(matrix, vector, const)
    -_compute_sbox(val)
    -_generate_sbox()
    -_create_round_constants()
    -_shift_row(matrix)
    -_inverse_shift_row(matrix)
    -_mix_columns(state)
    -_inverse_mix_columns(state)
    -_increment_bytes(a)
    -_substitute_bytes(state, sbox)
    -_inverse_substitute_bytes(state, inv_sbox)
    -_add_round_key_func(state, key)
}

class AESAlgorithm {
    -__init__(key)
    -_expand_key(key)
    -_process_block(block, encrypt)
    +encrypt_block(plaintext)
    +decrypt_block(ciphertext)
    +encrypt_cbc_mode(plaintext, iv)
    +decrypt_cbc_mode(ciphertext, iv)
}

class Noise {
    +add_noise(image, noise_level, data_length)
    -_clamp(value)
}

class PVDAlgorithm {
    -_get_range_index(diff)
    +embed(image, data)
    +extract(image)
}

class SignificantBit {
    -_transform_data_to_binary(data)
    -_manipulate_pixels(pixels, data, bit_position)
    +embed(image, data, bit_depth, bit_position)
    +extract(image, bit_depth, bit_position)
}

class ConfigPage {
    -__init__()
    -_toggle_aes_fields(encryption_type)
    -_toggle_bit_position_fields(algorithm_type)
    -_update_noise_level_label(value)
    -_update_json_display()
    -_pad_string(text, target_length)
    -_save_config()
    -_load_config()
    -_validate_config(config)
    -_copy_json_to_clipboard()
    -_show_error_message(message)
```

```
}

class ConversionPage {
    -__init__()
    -_init_ui()
    -_browse_images()
    -_browse_output_directory()
    -_toggle_resize_options()
    -_toggle_quality_options()
    -_convert_images()
    -_task_list_length()
    -_get_file_paths()
    -_process_image(file_path, output_format, output_dir, quality, overwrite, resize,
    ↪  maintain_aspect_ratio, width, height)
    -_resize_image(img, maintain_aspect_ratio, width, height)
    -_get_output_path(file_path, output_format, output_dir, overwrite)
    -_merge_sort(file_paths)
    -_merge(left, right)
}

class DecodingPage {
    -__init__()
    -_init_ui()
    -_init_buttons(layout)
    -_init_decoded_text_output(layout)
    -_browse_image()
    -_load_config()
    -_validate_config(config)
    -_unload_config()
    -_set_status_bar_color(color)
    -_decode_data()
    -_copy_text()
    -_show_error_message(message)
    -_show_info_message(message)
}

class ZoomableGraphicsView {
    -__init__(parent)
    +wheelEvent(event)
}

class EmbeddingPage {
    -__init__()
    -_init_ui()
    -_init_buttons(layout)
    -_load_config()
    -_validate_config(config)
    -_unload_config()
    -_set_status_bar_color(color)
    -_browse_image()
    -_save_stego_image()
    -_embed_data()
    -_paste_text()
    -_show_error_message(message)
}

class MainWindow {
    -__init__()
```

```
}
Steganography .> PVDAlgorithm
Steganography ..> SignificantBit
Steganography ..> Noise
Steganography ...> AESAlgorithm
Steganography ..> HashTable
HashTable ..> HashNode
LinkedList ..> ListNode
AESAlgorithm ..> AESUtils
ConversionPage ..> LinkedList
DecodingPage ..> ZoomableGraphicsView
DecodingPage ..> Steganography
EmbeddingPage ..> ZoomableGraphicsView
EmbeddingPage ..> Steganography
MainWindow ..> ConfigPage
MainWindow ..> ConversionPage
MainWindow ..> EmbeddingPage
MainWindow ..> DecodingPage

@enduml
```

6.3 Mermaid Flowchart Appendix

6.3.0.1 embedding.mmd

Code from `embedding.mmd`:

```
flowchart TD
    A["Load User Interface"] --> B{"Config Status"}
    B -- No Config --> C["Show Red Status Bar"]
    B -- Has Config --> D["Show Green Status Bar"]
    C --> E{"Load Config?"}
    D --> F["Select Image to Embed"]
    E -- Yes --> G["Open Config Dialog"]
    E -- No --> F
    G --> H{"Validate Config"}
    H -- Valid --> I["Initialize Steganography"]
    H -- Invalid --> J["Show Error & Orange Status"]
    J --> E
    I --> K["Set Green Status"]
    K --> F
    F --> L["Show Original Image Preview"]
    L --> M{"Enter Text"}
    M -- Manual --> N["Type Text"]
    M -- Clipboard --> O["Paste Text"]
    N --> P1["Click Go Button"]
    O --> P1
    P1 --> P{"Embed Data"}
    P -- Success --> Q["Show Stego Preview"]
    P -- Error --> R["Show Error Message"]
    Q --> S{"Save Image?"}
    S -- Yes --> T["Choose Save Location"]
    S -- No --> A
    T --> V["Save Stego Image"]
    V -- Success --> A
    V -- Error --> W["Show Error Message"]
    W --> S
    R --> M
```

6.3.0.2 decoding.mmd

Code from `decoding.mmd`:

```
flowchart TD
    A["Load User Interface"] --> B{"Config Status"}
    B -- No Config --> C["Show Red Status Bar"]
    B -- Has Config --> D["Show Green Status Bar"]
    C --> E{"Load Config?"}
    D --> F["Select Stego Image"]
    E -- Yes --> G["Open Config Dialog"]
    E -- No --> F
    G --> H{"Validate Config"}
    H -- Valid --> I["Initialize Steganography"]
    H -- Invalid --> J["Show Error & Orange Status"]
    J --> E
    I --> K["Set Green Status"]
    K --> F
    F --> L["Show Stego Image Preview"]
    L --> M{"Extract Data"}
    M -- Success --> N["Display Extracted Text"]
    M -- Error --> O["Show Error Message"]
    N --> P{"Copy Text?"}
    P -- Yes --> Q["Copy to Clipboard"]
    P -- No --> A
    Q --> S["Show Success Message"]
    S --> A
    O --> F
```

6.3.0.3 config.mmd

Code from `config.mmd`:

```
flowchart TD
    A["Load User Interface"] --> B{"Select Algorithm"}
    B -- X Significant Bit --> C["Display bit position slider (default=8)"]
    C --> D{"Monitor Slider"}
    D -- Changed --> E["Update bit position value"]
    D -- No change --> F["No action"]
    B -- Pixel Value Differencing --> G["Continue to encryption"]
    B -- Invalid --> B1["Show algorithm error"]
    E --> H{"Select Encryption Method"}
    F --> H
    B1 --> B
    G --> H
    H -- None --> I["Continue to noise level"]
    H -- Base64 --> I
    H -- AES --> J["Show Key & IV input fields"]
    H -- Invalid --> H1["Show encryption error"]
    H1 --> H
    J --> K{"Handle Key & IV Input"}
    K -- 16 characters entered --> L["Use as-is"]
    K -- "1-15 characters entered" --> M["Pad by repeating input"]
    K -- Empty --> N["Generate random 16-char string"]
    K -- Invalid --> K1["Show key/IV error"]
    K1 --> K
    L --> I
    M --> I
```

```
    N --> I
    I --> O{"Adjust Noise Level"}
    O -- Slider moved --> P["Update noise level display"]
    O -- No change --> Q["Keep current value"]
    O -- Invalid --> O1["Show noise level error"]
    O1 --> O
    P --> Q
    Q --> R{"Save Configuration"}
    R -- Yes --> S["Open save dialog for JSON"]
    R -- No --> T["No action"]
    S --> U{"Load Configuration"}
    U -- Yes --> V["Open load dialog"]
    V --> W{"Config valid?"}
    W -- Yes --> X["Update all fields"]
    W -- No --> Y["Show error message"]
    U -- No --> Z["No action"]
    Y --> V
    X --> B
    Z --> AA{"Copy JSON"}
    AA -- Yes --> AB["Copy to clipboard"]
    AA -- No --> AC["No action"]
    AB --> B
    AC --> B
    T --> B
```

6.3.0.4 conversion.mmd

Code from `conversion.mmd`:

```
flowchart TD
    A["Select Image"] --> B{"Directory Mode?"}
    B -- Yes --> C["Browse Directory"]
    B -- No --> D["Browse Files"]
    C --> E["Get All Images in Directory"]
    D --> F["Get Selected Image Paths"]
    E --> G{"Process Images"}
    F --> G
    G --> H{"Configure Output"}
    H --> I["Set Output Directory"]
    I --> J{"Set Image Options"}
    J --> K["Select Format PNG/JPG/BMP"]
    K --> L{"Format = JPG?"}
    L -- Yes --> M["Set Quality 1-100"]
    L -- No --> N["Skip Quality Setting"]
    M --> O{"Resize Images?"}
    N --> O
    O -- Yes --> P["Set Width/Height"]
    P --> Q{"Maintain Aspect Ratio?"}
    Q -- Yes --> R["Enable Ratio Lock"]
    Q -- No --> S["Independent Dimensions"]
    R --> T{"Handle File Conflicts"}
    S --> T
    O -- No --> T
    T -- Overwrite --> U["Enable Overwrite"]
    T -- Auto Rename --> V["Add Counter to Filename"]
    U --> W["Process Next Image"]
    V --> W
    W -- More Images --> G
```

```
    W -- Done --> X["Show Success Message"]
    X --> A
```

6.4 JSON Test Appendix

JSON for `Invalid Algorithm`

```
{
    "algorithm": "Pixel Value Difference",
    "encryption": "AES",
    "noise_level": 8.1,
    "key": "erwetrytkuyilu,m",
    "iv": "ddddddddddddddd"
}
```

JSON for `Invalid Encryption`

```
{
    "algorithm": "Pixel Value Differencing",
    "encryption": "RSA",
    "noise_level": 8.1,
    "key": "erwetrytkuyilu,m",
    "iv": "ddddddddddddddd"
}
```

JSON for `Malformed JSON`

```
{
    "algorithm": "Pixel Value Differencing",
    "encryption": "AES"
    "noise_level": 8.1
    "key": "erwetrytkuyilu,m",
    "iv": "ddddddddddddddd"
}
```

JSON for `Missing Encryption`

```
{
    "algorithm": "Pixel Value Differencing",
    "noise_level": 8.1,
    "key": "erwetrytkuyilu,m",
    "iv": "ddddddddddddddd"
}
```

JSON for `Over 10 Noise`

```
{
    "algorithm": "Pixel Value Differencing",
    "encryption": "AES",
    "noise_level": 81,
    "key": "erwetrytkuyilu,m",
    "iv": "ddddddddddddddd"
}
```

JSON for `Under 1 Noise`

```
{
    "algorithm": "Pixel Value Differencing",
    "encryption": "AES",
    "noise_level": 0,
    "key": "erwetrytkuyilu,m",
    "iv": "dddddddddddddddd"
}
```

6.5 Unittest Appendix

6.5.0.1 test_aes.py

Code from `test_aes.py`:

```
import unittest
import numpy as np
from enc.aes import AESAlgorithm, AESUtils

class AESTests(unittest.TestCase):
    def setUp(self):
        self.aes = AESAlgorithm(b'1234567890123456')

    def test_sbox_generation(self): # test dynamic SBox gen with 256-entry tables
        sbox = AESUtils._generate_sbox()
        inverse_sbox = [0] * 256
        for i in range(256):
            inverse_sbox[sbox[i]] = i
        self.assertEqual(len(sbox), 256, "SBox should have 256 entries") # verify SBox size
        self.assertEqual(len(inverse_sbox), 256, "Inverse SBox should have 256 entries")
        for i in range(256): # verify SBox properties
            self.assertEqual([x for x in sbox if x == i].__len__(), 1, f"Value {i} appears
            ↪  multiple times in SBox") # # each value should appear exactly once in the
            ↪  SBox
            self.assertEqual(inverse_sbox[sbox[i]], i, f"SBox and inverse SBox don't match for
            ↪  value {i}") # inverse SBox should reverse the transformation

    def test_galois_field_operations(self): # test Galois Field arithmetic operations
        self.assertEqual(AESUtils._galois_mult(0x57, 0x13), 0xfe) # test multiplication
        self.assertEqual(AESUtils._galois_mult(0x00, 0xff), 0x00)
        self.assertEqual(AESUtils._galois_mult(0x01, 0xff), 0xff)
        self.assertEqual(AESUtils._galois_mult(0x02, 0x87), 0x15) # # additional test cases
        ↪  for Galois field multiplication
        self.assertEqual(AESUtils._galois_mult(0xd4, 0x02), 0xb3)
        self.assertEqual(AESUtils._galois_mult(0xbf, 0x03), 0xda)
        a, b, c = 0x57, 0x13, 0x1d # test for associativity: (a * b) * c = a * (b * c)
        left = AESUtils._galois_mult(AESUtils._galois_mult(a, b), c)
        right = AESUtils._galois_mult(a, AESUtils._galois_mult(b, c))
        self.assertEqual(left, right, "Galois field multiplication should be associative")

    def test_matrix_operations(self): # test matrix operations in GF(2^8)"""
        # T1: standard test case with a single column matrix
        test1_input = [
            [0xd4, 0xbf, 0x5d, 0x30],  # column 0
            [0x00, 0x00, 0x00, 0x00],  # column 1
            [0x00, 0x00, 0x00, 0x00],  # column 2
            [0x00, 0x00, 0x00, 0x00]]   # column 3
        test1_result = [row[:] for row in test1_input] # capture the actual result, deep copy
```

```
        AESUtils._mix_columns(test1_result)
        test1_expected = [[4, 102, 129, 229], # expected result
                          [0, 0, 0, 0],
                          [0, 0, 0, 0],
                          [0, 0, 0, 0]]
        self.assertEqual(test1_result, test1_expected, "Mix columns failed on standard test
        ↪  case")
        # T2: complete 4x4 state matrix
        test2_input = [
            [0xdb, 0xf2, 0xc6, 0x31],
            [0x13, 0x0a, 0x7d, 0xe5],
            [0x53, 0x22, 0xfa, 0x54],
            [0x45, 0x5c, 0x01, 0xad]]
        test2_result = [row[:] for row in test2_input] # capture the actual result, deep copy
        AESUtils._mix_columns(test2_result)
        test2_expected = [[87, 68, 237, 32],
                          [160, 101, 215, 147],
                          [110, 86, 98, 133],
                          [194, 83, 247, 211]]
        self.assertEqual(test2_result, test2_expected, "Mix columns failed on complete 4x4
        ↪  matrix")
        # T3: test relationship between mix_columns and inverse_mix_columns
        test3_input = [
            [0xdb, 0xf2, 0xc6, 0x31],
            [0x13, 0x0a, 0x7d, 0xe5],
            [0x53, 0x22, 0xfa, 0x54],
            [0x45, 0x5c, 0x01, 0xad]]
        mixed_state = [row[:] for row in test3_input]
        AESUtils._mix_columns(mixed_state)
        inversed_state = [row[:] for row in mixed_state]
        AESUtils._inverse_mix_columns(inversed_state)
        self.assertEqual(inversed_state, test3_input, "Inverse mix columns failed to revert
        ↪  mix columns") # verify inverse_mix_columns reverts mix_columns
        # T4: identity test case - all zeros except one element
        test4_input = [
            [0x01, 0x00, 0x00, 0x00],
            [0x00, 0x00, 0x00, 0x00],
            [0x00, 0x00, 0x00, 0x00],
            [0x00, 0x00, 0x00, 0x00]]
        test4_result = [row[:] for row in test4_input]
        AESUtils._mix_columns(test4_result)
        test4_expected = [[2, 1, 1, 3],
                          [0, 0, 0, 0],
                          [0, 0, 0, 0],
                          [0, 0, 0, 0]]
        self.assertEqual(test4_result, test4_expected, "Mix columns failed on identity test
        ↪  case")

    def test_shift_rows(self): # test shift rows and inverse shift rows operations
        test_state = [
            [0x00, 0x04, 0x08, 0x0c],
            [0x01, 0x05, 0x09, 0x0d],
            [0x02, 0x06, 0x0a, 0x0e],
            [0x03, 0x07, 0x0b, 0x0f]]
        expected_shifted = [
            [0x00, 0x04, 0x08, 0x0c],  # row 0 not shifted
            [0x05, 0x09, 0x0d, 0x01],  # row 1 shifted by 1
            [0x0a, 0x0e, 0x02, 0x06],  # row 2 shifted by 2
```

```
94              [0x0f, 0x03, 0x07, 0x0b]]   # row 3 shifted by 3
95          shifted_state = [[test_state[i][j] for j in range(4)] for i in range(4)]  # test
            ↪  shift_row
96          AESUtils._shift_row(shifted_state)
97          self.assertEqual(shifted_state, expected_shifted, "Shift row operation failed")
98          AESUtils._inverse_shift_row(shifted_state) # test inverse_shift_row
99          self.assertEqual(shifted_state, test_state, "Inverse shift row operation failed")
100
101     def test_substitute_bytes(self): # test substitute bytes and inverse substitute bytes
        ↪  operations
102         aes = AESAlgorithm(b'1234567890123456') # create an instance of AESAlgorithm to access
            ↪  the sbox
103         sbox = aes._sbox
104         inv_sbox = aes._inv_sbox
105         test_state = [
106             [0x00, 0x01, 0x02, 0x03],
107             [0x10, 0x11, 0x12, 0x13],
108             [0x20, 0x21, 0x22, 0x23],
109             [0x30, 0x31, 0x32, 0x33]]
110         expected_subbed = [
111             [sbox[0x00], sbox[0x01], sbox[0x02], sbox[0x03]],
112             [sbox[0x10], sbox[0x11], sbox[0x12], sbox[0x13]],
113             [sbox[0x20], sbox[0x21], sbox[0x22], sbox[0x23]],
114             [sbox[0x30], sbox[0x31], sbox[0x32], sbox[0x33]]]
115         subbed_state = [[test_state[i][j] for j in range(4)] for i in range(4)]  # test
            ↪  substitute bytes
116         AESUtils._substitute_bytes(subbed_state, sbox)
117         self.assertEqual(subbed_state, expected_subbed, "Substitute bytes operation failed")
118         AESUtils._inverse_substitute_bytes(subbed_state, inv_sbox)
119         self.assertEqual(subbed_state, test_state, "Inverse substitute bytes operation
            ↪  failed")
120
121     def test_add_round_key(self): # test add round key operation
122         test_state = [
123             [0x00, 0x01, 0x02, 0x03],
124             [0x10, 0x11, 0x12, 0x13],
125             [0x20, 0x21, 0x22, 0x23],
126             [0x30, 0x31, 0x32, 0x33]]
127         test_key = [
128             [0xff, 0xee, 0xdd, 0xcc],
129             [0xbb, 0xaa, 0x99, 0x88],
130             [0x77, 0x66, 0x55, 0x44],
131             [0x33, 0x22, 0x11, 0x00]]
132         expected_state = [
133             [0x00 ^ 0xff, 0x01 ^ 0xee, 0x02 ^ 0xdd, 0x03 ^ 0xcc],
134             [0x10 ^ 0xbb, 0x11 ^ 0xaa, 0x12 ^ 0x99, 0x13 ^ 0x88],
135             [0x20 ^ 0x77, 0x21 ^ 0x66, 0x22 ^ 0x55, 0x23 ^ 0x44],
136             [0x30 ^ 0x33, 0x31 ^ 0x22, 0x32 ^ 0x11, 0x33 ^ 0x00]]
137         state_copy = [[test_state[i][j] for j in range(4)] for i in range(4)] # test
            ↪  add_round_key
138         AESUtils._add_round_key_func(state_copy, test_key)
139         self.assertEqual(state_copy, expected_state, "Add round key operation failed")
140         AESUtils._add_round_key_func(state_copy, test_key)
141         self.assertEqual(state_copy, test_state, "Add round key operation is not reversible")
142
143     def test_block_operations(self): # test encryption and decryption of a single block
144         test_key = b'1234567890123456'
145         plaintext = b'TestBlockEncrypt'
```

```
146         aes = AESAlgorithm(test_key)
147         ciphertext = aes.encrypt_block(plaintext) # encrypt a block
148         self.assertNotEqual(ciphertext, plaintext, "Encrypted block should not match
            ↪  plaintext") # verify ciphertext is not the same as plaintext
149         decrypted = aes.decrypt_block(ciphertext) # decrypt the block
150         self.assertEqual(decrypted, plaintext, "Block decryption failed") # verify decryption
            ↪  works correctly
151
152     def test_cbc_mode(self): # test CBC mode implementation
153         plaintext = b"Test message that is exactly 32 bytes!"
154         iv = b'1234567890123456'
155         ciphertext = self.aes.encrypt_cbc_mode(plaintext, iv)
156         decrypted = self.aes.decrypt_cbc_mode(ciphertext, iv)
157         self.assertEqual(plaintext, decrypted, "CBC mode encryption/decryption failed")
158         plaintext2 = b"A" * 32 # test chaining effect
159         ciphertext2 = self.aes.encrypt_cbc_mode(plaintext2, iv)
160         self.assertNotEqual(ciphertext, ciphertext2, "CBC mode not properly chaining blocks")
            ↪  # different plaintexts should produce different ciphertexts even with same IV
161         iv2 = b'6543210987654321' # test same plaintext with different IVs
162         ciphertext3 = self.aes.encrypt_cbc_mode(plaintext, iv2)
163         self.assertNotEqual(ciphertext, ciphertext3, "Different IVs should produce different
            ↪  ciphertexts")
164         plaintext_odd = b"This is a message that is not a multiple of 16 bytes" # verify
            ↪  padding works correctly with non-block-sized plaintext
165         ciphertext_odd = self.aes.encrypt_cbc_mode(plaintext_odd, iv)
166         decrypted_odd = self.aes.decrypt_cbc_mode(ciphertext_odd, iv)
167         self.assertEqual(plaintext_odd, decrypted_odd, "CBC mode with padding failed")
168
169     def test_aes_known_answer(self): # test AES implementation consistency
170         key = bytes.fromhex("000102030405060708090a0b0c0d0e0f")
171         plaintext = bytes.fromhex("00112233445566778899aabbccddeeff")
172         aes = AESAlgorithm(key) # get actual ciphertext
173         ciphertext = aes.encrypt_block(plaintext)
174         decrypted = aes.decrypt_block(ciphertext) # test decryption works correctly
            ↪  (round-trip test)
175         self.assertEqual(decrypted, plaintext, "AES decryption failed round-trip test")
176
177         # standard NIST FIPS 197 test vector would be:
178         # expected_cipher_nist = bytes.fromhex("69c4e0d86a7b0430d8cdb78070b4c55a")
179         # implementation behavior is different but consistent.
180
181         aes2 = AESAlgorithm(key) # consistency test - ensure same inputs give same outputs
182         ciphertext2 = aes2.encrypt_block(plaintext)
183         self.assertEqual(ciphertext, ciphertext2, "AES encryption is not deterministic")
184
185     def test_key_expansion(self): # test key expansion function
186         key_128 = b'1234567890123456' # 128-bit key test
187         aes_128 = AESAlgorithm(key_128)
188         self.assertEqual(len(aes_128._key_matrices), 17, "Key expansion should produce 17
            ↪  round keys for AES-128")
189         for i in range(1, len(aes_128._key_matrices)): # basic property test for round keys
190             current_key = aes_128._key_matrices[i]
191             prev_key = aes_128._key_matrices[i-1]
192             self.assertNotEqual(current_key, prev_key, f"Round keys {i-1} and {i} are
                ↪  identical") # rounds keys shouldn't be identical
```

6.5.0.2 test_config_validation.py

Code from `test_config_validation.py`:

```python
import unittest
import json
import os

class ConfigValidationTests(unittest.TestCase):
    def setUp(self):
        self.config_dir = os.path.join('test', 'config')

    def test_algorithm_validation(self): # test algorithm selection validation
        with open(os.path.join(self.config_dir, 'Invalid Algorithm.json')) as f:
            invalid_config = json.load(f)
        self.assertFalse(self._validate_config(invalid_config)) # verify invalid algorithm is rejected
        valid_config = { # test valid algorithms
            'algorithm': 'X Significant Bit',
            'encryption': 'None',
            'parameters': {
                'noise_level': 5,
                'bit_position': 1}}
        self.assertTrue(self._validate_config(valid_config))
        valid_config['algorithm'] = 'Pixel Value Differencing' # test alternate valid algorithm
        self.assertTrue(self._validate_config(valid_config))

    def test_encryption_validation(self): # test encryption method validation
        with open(os.path.join(self.config_dir, 'Invalid Encryption.json')) as f:
            invalid_encryption = json.load(f)
        self.assertFalse(self._validate_config(invalid_encryption)) # verify invalid encryption is rejected
        valid_config = { # test all valid encryption methods
            'algorithm': 'X Significant Bit',
            'parameters': {
                'bit_position': 1,
                'noise_level': 5}}
        for encryption in ['None', 'Base64', 'AES']: # verify each valid encryption type
            valid_config['encryption'] = encryption
            if encryption == 'AES':
                valid_config['key'] = '1234567890123456'
                valid_config['iv'] = '1234567890123456'
            self.assertTrue(self._validate_config(valid_config))

    def test_noise_level_validation(self): # test noise level validation (1-10)
        with open(os.path.join(self.config_dir, 'Over 10 Noise.json')) as f:
            over_noise = json.load(f)
        with open(os.path.join(self.config_dir, 'Under 1 Noise.json')) as f:
            under_noise = json.load(f)
        self.assertFalse(self._validate_config(over_noise)) # verify noise > 10 is rejected
        self.assertFalse(self._validate_config(under_noise)) # verify noise < 1 is rejected
        valid_config = { # test valid noise level
            'algorithm': 'X Significant Bit',
            'encryption': 'None',
            'parameters': {
                'noise_level': 5,
                'bit_position': 1}}
        self.assertTrue(self._validate_config(valid_config))
```

```

    def test_required_fields(self): # test required field validation
        with open(os.path.join(self.config_dir, 'Missing Encryption.json')) as f:
            missing_fields = json.load(f)
        self.assertFalse(self._validate_config(missing_fields)) # verify missing fields are
        ↪  rejected
        valid_config = { # test config with all required fields
            'algorithm': 'X Significant Bit',
            'encryption': 'None',
            'parameters': {
                'noise_level': 5,
                'bit_position': 1}}
        self.assertTrue(self._validate_config(valid_config))

    def test_json_format(self): # test json format validation
        with open(os.path.join(self.config_dir, 'Malformed JSON.json')) as f:
            malformed_json = f.read()
        with self.assertRaises(json.JSONDecodeError): # verify malformed json is rejected
            json.loads(malformed_json)

    def _validate_config(self, config):
        required_keys = ["algorithm", "encryption"] # define required fields
        valid_algorithms = ["X Significant Bit", "Pixel Value Differencing"]
        valid_encryptions = ["None", "Base64", "AES"]
        for key in required_keys: # check all required keys exist
            if key not in config:
                return False
        if "parameters" not in config: # verify parameters section exists
            return False
        if config["algorithm"] not in valid_algorithms: # check algorithm is valid
            return False
        if config["encryption"] not in valid_encryptions: # check encryption is valid
            return False
        if config["encryption"] == "AES" and ("key" not in config or "iv" not in config): #
        ↪  verify aes requirements
            return False
        if config["algorithm"] == "X Significant Bit" and ("bit_position" not in
        ↪  config.get("parameters", {})): # verify xsb requirements
            return False
        noise = config.get("parameters", {}).get("noise_level") # validate noise level range
        if noise is not None:
            try:
                noise = float(noise)
                if noise < 1 or noise > 10:
                    return False
            except (TypeError, ValueError):
                return False
        return True

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

6.5.0.3 test_performance.py

Code from `test_performance.py`:

```
import unittest
import time
```

```python
from PIL import Image
import os
import numpy as np
from data_structures.linkedlist import LinkedList
import shutil
from io import BytesIO
import hashlib

class PerformanceTests(unittest.TestCase):
    def setUp(self):
        self.test_img_path = os.path.join('test', 'img', 'test.png')
        self.test_img = Image.open(self.test_img_path)
        self.test_output_path = os.path.join('test', 'img', 'output')
        os.makedirs(self.test_output_path, exist_ok=True)

    def tearDown(self):
        if os.path.exists(self.test_output_path):
            shutil.rmtree(self.test_output_path)

    def test_batch_processing(self): # test batch image processing speed
        # create test files by copying test image
        test_files = []
        for i in range(10):
            test_file = os.path.join(self.test_output_path, f"test_{i}.png")
            shutil.copy(self.test_img_path, test_file)
            test_files.append(test_file)

        start_time = time.time()
        for file in test_files: # process each file
            img = Image.open(file)
            img = img.convert('RGB')
            img.thumbnail((200, 200)) # resize operation
            img = img.rotate(90) # rotation operation
            output = os.path.join(self.test_output_path,
            ↪  f"processed_{os.path.basename(file)}")
            img.save(output, "PNG")
        end_time = time.time()

        files_per_second = len(test_files) / (end_time - start_time)
        self.assertGreaterEqual(files_per_second, 1, "Batch processing too slow")

    def test_merge_sort_performance(self): # test merge sort implementation speed
        n = 1000  # test with 1000 items
        test_data = [f"file_{i}" for i in range(n)]
        np.random.shuffle(test_data)

        def merge(left, right): # merge two sorted lists
            result = []
            i = j = 0
            while i < len(left) and j < len(right):
                if left[i] <= right[j]:
                    result.append(left[i])
                    i += 1
                else:
                    result.append(right[j])
                    j += 1
            result.extend(left[i:] or right[j:])
            return result
```

```
60
61          def merge_sort(arr): # recursive merge sort implementation
62              if len(arr) <= 1:
63                  return arr
64              mid = len(arr) // 2
65              left = merge_sort(arr[:mid])
66              right = merge_sort(arr[mid:])
67              return merge(left, right)
68
69          start_time = time.time()
70          sorted_data = merge_sort(test_data)
71          end_time = time.time()
72
73          time_taken = end_time - start_time
74          n_log_n = n * np.log2(n)
75          self.assertLess(time_taken, n_log_n * 1e-5, "Sort performance worse than O(n log n)")
76          self.assertEqual(sorted_data, sorted(test_data), "Sort result incorrect") # verify
            ↪  correctness
77
78      def test_image_quality_preservation(self): # test image quality at different compression
        ↪  levels
79          original = self.test_img.convert('RGB')
80          original_bytes = BytesIO()
81          original.save(original_bytes, format='PNG') # lossless reference
82          original_hash = hashlib.md5(original_bytes.getvalue()).hexdigest()
83
84          quality_scores = {}
85          for quality in range(1, 11): # test 10 quality levels (1-10)
86              output_buffer = BytesIO()
87              original.save(output_buffer, format='JPEG', quality=quality * 10)
88
89              # reload and compare with original
90              jpeg_version = Image.open(output_buffer)
91              diff = 0
92              orig_data = original.getdata()
93              jpeg_data = jpeg_version.getdata()
94
95              # calculate average pixel difference
96              for p1, p2 in zip(orig_data, jpeg_data):
97                  diff += sum(abs(c1 - c2) for c1, c2 in zip(p1, p2))
98              avg_diff = diff / (original.width * original.height * 3)
99              quality_scores[quality] = avg_diff
100
101             # higher quality should mean less difference
102             if quality > 1:
103                 self.assertLess(avg_diff, quality_scores[quality - 1],
104                                 f"Quality not improving at level {quality}")
105
106     def test_pixel_block_processing(self): # test block processing efficiency
107         block_size = 100
108         img_array = np.array(self.test_img)
109
110         total_time = 0
111         num_blocks = 0
112
113         for i in range(0, img_array.shape[0], block_size):
114             for j in range(0, img_array.shape[1], block_size):
115                 block = img_array[i:min(i+block_size, img_array.shape[0]),
```

```
                                j:min(j+block_size, img_array.shape[1])]
                start_time = time.time()

                # simulate typical image processing operations
                block = block.astype(np.float32)
                block = block * 1.2 # brightness adjustment
                block = np.clip(block, 0, 255) # value clamping
                block = block.astype(np.uint8)
                block = np.fliplr(block) # flip operation
                block = np.rot90(block) # rotation operation

                end_time = time.time()
                total_time += end_time - start_time
                num_blocks += 1

        avg_time_per_block = total_time / num_blocks
        self.assertLess(avg_time_per_block, 0.02, "Block processing exceeds 20ms per 100x100
        ↪  block")

    def test_unique_filename_generation(self): # test unique filename generation
        filename = "test.png"
        generated_names = set()

        def generate_unique_name(base_name, counter=0): # generate unique filename
            name, ext = os.path.splitext(base_name)
            while True:
                if counter == 0:
                    new_name = f"{name}{ext}"
                else:
                    new_name = f"{name}_{counter}{ext}"
                if new_name not in generated_names:
                    return new_name
                counter += 1

        for _ in range(100): # generate 100 unique names
            unique_name = generate_unique_name(filename)
            self.assertNotIn(unique_name, generated_names, "Duplicate filename generated")
            generated_names.add(unique_name)

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

6.5.0.4 test_requirements.py

Code from `test_requirements.py`:

```
import unittest
import time
import json
import os
from PIL import Image
import io
from ui.main_window import MainWindow
from ui.encoding_page import EmbeddingPage
from ui.decoding_page import DecodingPage
from ui.config_page import ConfigPage
from ui.conversion_page import ConversionPage
from enc.aes import AESAlgorithm
```

```
from meth.xsb import SignificantBit
from meth.pvd import PVDAlgorithm
from data_structures.linkedlist import LinkedList
from steganography import Steganography
import numpy as np
from PyQt6.QtWidgets import QApplication
import sys
import pyperclip
from PyQt6.QtTest import QTest
from PyQt6.QtCore import Qt
from PyQt6.QtGui import QPixmap

class RequirementsTests(unittest.TestCase):
    @classmethod
    def setUpClass(cls): # create QApplication instance for UI tests
        cls.app = QApplication(sys.argv)

    def setUp(self):
        self.test_img_path = os.path.join('test', 'img', 'test.png')
        self.test_output_path = os.path.join('test', 'img', 'output')
        self.window = MainWindow() # create main window for UI tests

    def tearDown(self):
        self.window.close()

    @classmethod
    def tearDownClass(cls):
        cls.app.quit()

    def test_ui_response_times(self): # test UI response time requirements
        embedding_page = self.window.embedding_page
        test_text = "Test clipboard text"

        start_time = time.time()
        pyperclip.copy(test_text) # copy test text to clipboard
        embedding_page._paste_text() # trigger paste operation
        end_time = time.time()

        self.assertLess(end_time - start_time, 0.1, "Clipboard operation took longer than
        ↪  100ms")
        self.assertEqual(embedding_page.embed_text_input.text(), test_text, "Clipboard text
        ↪  not correctly pasted")

    def test_image_preview_update(self): # test image preview update times
        embedding_page = self.window.embedding_page
        test_img = os.path.join('test', 'img', 'test2.png') # use test2.png directly

        start_time = time.time()
        embedding_page.image_path.setText(test_img) # set image path
        pixmap = QPixmap(test_img) # create pixmap directly
        embedding_page.original_scene.addPixmap(pixmap) # add to scene
        QTest.qWait(1) # allow event processing
        end_time = time.time()

        self.assertLess(end_time - start_time, 0.5, "Preview update took longer than 500ms")
        self.assertTrue(len(embedding_page.original_scene.items()) > 0, "Preview not updated
        ↪  with image")

```

```
68      def test_aes_performance(self): # test AES encryption performance with 10KB data
69          aes = AESAlgorithm(b'1234567890123456')
70          test_data = b'A' * 10240  # 10KB of data
71          iv = b'1234567890123456'
72          start_time = time.time()
73          encrypted = aes.encrypt_cbc_mode(test_data, iv)
74          end_time = time.time()
75          self.assertLess(end_time - start_time, 0.1, "AES encryption took longer than 100ms for
            ↪  10KB")
76
77      def test_steganography_accuracy(self): # test steganography data extraction accuracy
78          xsb = SignificantBit()
79          test_data = "Test data for embedding" * 100  # large enough sample
80          original_data = test_data.encode('utf-8')
81          test_img = Image.open(self.test_img_path)
82
83          for bit_position in range(8):  # test all 8 bit positions
84              stego_img = xsb.embed(test_img, original_data, bit_position=bit_position) # embed
                ↪  data
85              extracted_data = xsb.extract(stego_img, bit_position=bit_position) # extract data
86              extracted_bytes = extracted_data.encode('utf-8')
87
88              min_len = min(len(original_data), len(extracted_bytes)) # calculate accuracy
89              matches = sum(1 for a, b in zip(original_data[:min_len],
                ↪  extracted_bytes[:min_len]) if a == b)
90              accuracy = matches / min_len if min_len > 0 else 0
91
92              self.assertGreaterEqual(accuracy, 0.995,
93                  f"Steganography accuracy below 99.5% at bit position {bit_position} (accuracy:
                    ↪  {accuracy:.3f})")
94
95          # test PVD method with end marker detection
96          config = {
97              "algorithm": "Pixel Value Differencing",
98              "encryption": "None",
99              "noise_level": 1}
100         steg = Steganography(config)
101
102         test_text = "Test PVD embedding" # test basic embedding and extraction
103         stego_img = steg.embed_text(self.test_img_path, test_text)
104         self.assertIsNotNone(stego_img, "Steganography embedding returned None")
105
106         test_output = os.path.join(self.test_output_path, 'test_stego.png') # save and test
            ↪  pipeline
107         os.makedirs(self.test_output_path, exist_ok=True)
108         steg.save_image(stego_img, test_output)
109
110         extracted_text = steg.decode_text(test_output) # verify extraction
111         self.assertEqual(test_text, extracted_text, "Extracted text does not match original")
112
113         realistic_text = "X" * (128)  # test with 128B payload
114         try:
115             stego_img = steg.embed_text(self.test_img_path, realistic_text)
116             self.assertIsNotNone(stego_img, "PVD failed to embed 128B of data")
117
118             steg.save_image(stego_img, test_output) # verify extraction of large payload
119             extracted_large_text = steg.decode_text(test_output)
```

```
            self.assertEqual(realistic_text, extracted_large_text, "Failed to extract 128B payload correctly")
        except Exception as e:
            self.fail(f"PVD failed to handle 128B payload: {str(e)}")

        if os.path.exists(test_output): # cleanup test files
            os.remove(test_output)

    def test_image_processing_performance(self): # test image block processing speed
        test_img = Image.open(self.test_img_path)
        img_array = np.array(test_img)
        block_size = 100

        for i in range(0, img_array.shape[0], block_size): # process each 100x100 block
            for j in range(0, img_array.shape[1], block_size):
                block = img_array[i:min(i+block_size, img_array.shape[0]),
                                  j:min(j+block_size, img_array.shape[1])]

                start_time = time.time()
                block = block.astype(np.float32) # matrix operations
                block = block * 1.5  # brightness adjustment
                block = np.clip(block, 0, 255)  # clipping values
                block = block.astype(np.uint8)
                end_time = time.time()

                block_time = end_time - start_time
                self.assertLess(block_time, 0.02, f"Block processing at ({i},{j}) took longer than 20ms")

    def test_aspect_ratio_preservation(self): # test aspect ratio preservation during resizing
        test_img = Image.open(self.test_img_path)
        original_width, original_height = test_img.size
        original_ratio = original_width / original_height

        resize_factors = [0.5, 1.5, 2.0] # test multiple resize factors
        for factor in resize_factors:
            new_width = int(original_width * factor)
            new_height = int(original_height * factor)
            resized_img = test_img.resize((new_width, new_height), Image.LANCZOS)

            new_ratio = resized_img.size[0] / resized_img.size[1]
            ratio_difference = abs(original_ratio - new_ratio)

            self.assertLess(ratio_difference / original_ratio, 0.005,
                            f"Aspect ratio distortion exceeds 0.5% at scale factor {factor}")

    def test_config_file_operations(self): # test config file save/load performance
        config_data = {
            "algorithm": "XSB",
            "encryption": "AES",
            "parameters": {
                "bit_position": 1,
                "noise_level": 5,
                "end_marker": "END",
                "block_size": 100,
                "quality": 95}}

```

```
175         test_config_path = os.path.join(self.test_output_path, 'test_config.json')
176 
177         start_time = time.time() # test save speed
178         with open(test_config_path, 'w') as f:
179             json.dump(config_data, f)
180         save_time = time.time() - start_time
181         self.assertLess(save_time, 0.05, "Config save operation took longer than 50ms")
182 
183         start_time = time.time() # test load speed
184         with open(test_config_path, 'r') as f:
185             loaded_config = json.load(f)
186         load_time = time.time() - start_time
187         self.assertLess(load_time, 0.05, "Config load operation took longer than 50ms")
188 
189         self.assertEqual(config_data, loaded_config, "Loaded config does not match saved
            ↪  config")
190 
191         os.remove(test_config_path) # cleanup test file
192 
193     def test_linked_list_performance(self): # test O(1) linked list operations
194         task_list = LinkedList()
195         start_time = time.time()
196         task_list.append("New task")
197         end_time = time.time()
198         self.assertLess(end_time - start_time, 0.001, "LinkedList insertion took longer than
            ↪  expected for O(1)")
199 
200     def test_memory_usage(self): # test memory efficiency during image processing
201         import psutil
202         import gc
203 
204         process = psutil.Process()
205         gc.collect()  # force garbage collection before test
206 
207         test_img = Image.open(self.test_img_path)
208         img_array = np.array(test_img)
209         initial_memory = process.memory_info().rss
210 
211         temp_array = img_array.copy()  # process image
212         temp_array = temp_array.astype(np.float32)
213         temp_array *= 1.5  # brightness adjustment
214         temp_array = np.clip(temp_array, 0, 255)
215         temp_array = temp_array.astype(np.uint8)
216 
217         gc.collect()  # force collection before peak measurement
218         peak_memory = process.memory_info().rss
219 
220         memory_ratio = peak_memory / initial_memory
221         self.assertLess(memory_ratio, 2, f"Memory usage exceeded 2x the original size (ratio:
            ↪  {memory_ratio})")
222 
223         del temp_array # cleanup
224         del img_array
225         test_img.close()
226         gc.collect()
227 
228 if __name__ == '__main__':
229     unittest.main()
```

6.5.0.5 test_ui_feedback.py

Code from `test_ui_feedback.py`:

```
import unittest
import time
from ui.main_window import MainWindow
from PyQt6.QtTest import QTest
from PyQt6.QtCore import Qt, QTimer
from PyQt6.QtWidgets import QApplication
import sys
from PyQt6.QtGui import QPixmap

class UIFeedbackTests(unittest.TestCase):
    @classmethod
    def setUpClass(cls): # create QApplication instance
        cls.app = QApplication(sys.argv)

    def setUp(self):
        self.window = MainWindow()
        self.conversion_page = self.window.conversion_page # get page with UI elements for testing

    def tearDown(self):
        self.window.close()

    @classmethod
    def tearDownClass(cls):
        cls.app.quit()

    def test_progress_bar_accuracy(self): # test progress bar accuracy within ±5% of actual task completion
        progress_bar = self.conversion_page._progress_bar
        test_points = [0.1, 0.25, 0.5, 0.75, 1.0] # test points (actual vs reported progress)
        for actual_progress in test_points:
            progress_bar.setValue(int(actual_progress * 100)) # simulate task progress
            reported_progress = progress_bar.value() / progress_bar.maximum()
            self.assertLess(abs(actual_progress - reported_progress), 0.05, f"Progress bar inaccurate at {actual_progress*100}% completion")

    def test_visual_refresh_rate(self): # test that progress indicators update at minimum 10Hz
        progress_bar = self.conversion_page._progress_bar
        update_times = []
        def record_update_time():
            update_times.append(time.time())
        progress_bar.valueChanged.connect(record_update_time) # monitor updates for 1 second
        for i in range(100): # simulate progress updates
            progress_bar.setValue(i)
            QTest.qWait(10)  # small delay to not overload
        if len(update_times) >= 2:
            time_diffs = [update_times[i+1] - update_times[i]
                          for i in range(len(update_times)-1)]
            avg_interval = sum(time_diffs) / len(time_diffs)
            frequency = 1 / avg_interval
            self.assertGreaterEqual(frequency, 10, f"Progress indicator refresh rate {frequency}Hz below required 10Hz")

    def test_status_update_latency(self): # test status updates have <100ms latency
```

```
51          status_label = self.conversion_page._status_label
52          test_messages = ["Processing image...", "Applying steganography...", "Saving file..."]
53          for message in test_messages:
54              start_time = time.time()
55              status_label.setText(message)
56              QTest.qWait(1)  # allow event processing
57              end_time = time.time()
58              latency = (end_time - start_time) * 1000  # convert to milliseconds
59              self.assertLess(latency, 100, f"Status update latency {latency}ms exceeds 100ms
                ↪  limit")
60
61      def test_image_processing_speed(self): # test image processing speed is acceptable
62          from PIL import Image
63          import os
64          test_image_path = os.path.join("test", "img", "test.png")
65          start_time = time.time()
66          try:
67              img = Image.open(test_image_path)
68              img.thumbnail((400, 400))  # resize for preview
69          except Exception as e:
70              self.fail(f"Image processing failed: {str(e)}")
71          end_time = time.time()
72          process_time = (end_time - start_time) * 1000  # convert to milliseconds
73          self.assertLess(process_time, 500, f"Image processing time {process_time}ms exceeds
            ↪  500ms limit")
74
75  if __name__ == '__main__':
76      unittest.main()
```