

**AN INTELLIGENT SYSTEM FOR DETECTION,
TRANSLATION, AND HISTORICAL MAPPING OF
ANCIENT INSCRIPTIONS**

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April 2026

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DECLARATION

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The above candidate has carried out research for the bachelor's degree Dissertation under my supervision.

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Name of Co-Supervisor: Mr. Samadhi Rathnayake

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to all those who supported and guided me throughout the completion of this project.

First and foremost, I extend my deepest appreciation to my supervisor for their continuous guidance, valuable insights, and constructive feedback throughout the development of this research. Their expertise and encouragement played a crucial role in shaping the direction and quality of this work.

I would also like to thank the academic staff of the Sri Lanka Institute of Information Technology (SLIIT) for providing the necessary knowledge, resources, and support required to successfully complete this project. Their dedication to teaching and learning has greatly contributed to my academic growth.

My heartfelt gratitude goes to my friends and peers who provided support, shared ideas, and assisted me during various stages of this project. Their encouragement and collaboration were invaluable.

Finally, I would like to express my deepest thanks to my family for their unwavering support, understanding, and motivation throughout my academic journey. Their constant encouragement has been a source of strength and inspiration.

ABSTRACT

The analysis of inscription images remains a challenging problem in the domain of computer vision due to the presence of degradation factors such as noise, low contrast, surface erosion, and uneven illumination. While traditional image processing techniques have shown their ineffectiveness to provide adequate results without loss of structural information, the current research aims to overcome these drawbacks by proposing an enhanced version of image processing techniques. More specifically, it introduces a pipeline combining preprocessing steps with segmentation techniques to facilitate character extraction from inscriptions. First of all, it should be noted that this image processing procedure implies consecutive performance of several procedures on an input image. Thus, such preprocessing steps as gray-scale transformation, noise reduction, and contrast enhancement will take place. Moreover, after that, image sharpening algorithms will be applied (for example, based on Laplacian edge enhancements). Afterwards, adaptive thresholding techniques will be employed to separate foregrounds from backgrounds in different lighting conditions. As far as character segmentation goes, contour detection methods will be used to isolate specific character areas from other areas of interest. In addition, connected components analysis will be performed to ensure proper isolation of characters. Other processing methods, such as noise reduction, bounding box refining, and size standardization will take place to achieve higher accuracy levels. It is expected that the above-described algorithm would help to enhance both the accuracy of the segmentation and the edge detection in order to provide adequate character segmentation. In addition, the application of image sharpening technique shows higher robustness than using only preprocessing methods. Finally, the output of this process will be structured as a set of images showing isolated characters. Thus, the current research shows that the proposed image processing solution provides a contribution to the development of automated inscriptions analyses. In particular, it provides better accuracy when applying the described techniques. Therefore, the application of these methods could be beneficial for intelligent document analysis and automatic digital preservation of artifacts.

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LIST OF ABBREVIATIONS

1. INTRODUCTION

The extraction and processing of text information from inscription images has gained increasing importance in the areas of computer vision, digital preservation, and archeology. Historical inscriptions captured in digital images often suffer severe visual distortion due to various environmental conditions, age-related changes, deterioration, and irregularity of illumination. Noise, poor contrast, fuzzy edges, and non-uniform backgrounds are among other characteristics of degraded images, which pose a challenge for accurate detection of individual characters.

As part of pre-recognition procedures, character segmentation plays a crucial role in the analysis of inscriptions since it serves as a basis for subsequent steps. However, as mentioned above, the performance of character segmentation algorithms largely depends on image quality. Conventional image processing techniques cannot simultaneously reduce noise and keep fine structural details intact, thus resulting in imprecise boundaries of characters.

In their efforts to improve image quality and prepare the source material for further analysis, scientists have been developing image enhancement techniques. In particular, edge-preserving enhancement techniques that include sharpening have recently proven to be beneficial for preserving structural details in degraded images. In turn, adaptive binarization helps to isolate the foreground characters regardless of varying illumination and background irregularities.

This research paper outlines an integrated image processing solution consisting of preprocessing and post-processing phases, image sharpening technique, and adaptive binarization and segmentation procedures. The described algorithm is developed with the aim of improving the accuracy of character extraction by strengthening contours and providing a robust way of isolating individual characters. In addition, a combination of contour and connected components segmentation methods allows for achieving more accurate results.

Thus, one of the main contributions of this work is an advanced image enhancement approach based on the sharpening technique combined with adaptive character segmentation. Through edge enhancement and adaptive segmentation, it is expected that

the performance of the algorithm will be improved and provide for higher accuracy of character extraction from inscription images.

1.1. Background & Literature Survey

1.1.1. Image Quality as a Measurable Property in Image Processing Systems

As far as image processing systems are concerned, the quality of an image is the most important parameter that can be easily measured. When we deal with character extraction and other operations based on image processing, the image quality becomes especially important due to numerous distortions caused by noise, low contrast, surface erosion, and uneven illumination. Thus, evaluating and improving the quality of image is a necessary step before performing any operation with it.

The quality of an image can be defined objectively or subjectively. The former means measuring some parameters, including SNR, image contrast and sharpness, whereas the latter implies evaluating the readability and interpretability of the characters within it. Objective estimation allows us to create a certain standard for image processing. As far as characters segmentation is concerned, the two main parameters that affect its results are edge sharpness and contrast. Thus, fragmentation or merging of character segments can be easily explained with poor image quality, and various enhancement techniques should be applied to solve this problem. Image sharpening is one of such techniques aimed at improving edge detection accuracy.

On top of that, the technique of binarization, i.e. separating the characters from the background, strongly depends on the image quality. One of the latest advances in binarization techniques is adaptive thresholding, which allows to perform it even when there are significant variations of illumination present in the image.

In conclusion, treating image quality as a measurable parameter leads to better results since this way we can enhance it using specific operations, like sharpening.

Table 1: Evolution of Usability Analysis Techniques and Key Technological Milestones

Year/Period	Research Focus	Key Technologies	Limitations Addressed	Remaining Gaps
Early 2000s	Basic image preprocessing	Histogram Equalization, Filtering	Improved contrast and noise reduction	Poor handling of complex backgrounds
2010–2015	Thresholding-based segmentation	Otsu’s Method, Global Thresholding	Simple foreground-background separation	Sensitive to lighting variations
2015–2018	Edge detection & contour methods	OpenCV, Canny Edge Detector	Improved boundary detection	Broken edges in degraded images
2018–2020	Adaptive binarization techniques	Adaptive Thresholding, Morphological Operations	Better handling of uneven illumination	Noise still affects segmentation accuracy
2020–2022	Machine learning-based segmentation	SVM, Basic CNNs	Improved classification of character regions	Requires labeled data, limited generalization
2022–Present	Deep learning-based approaches	CNN, U-Net, TensorFlow/Keras	High accuracy in segmentation tasks	Computational complexity, data dependency
Proposed System	Sharpening-based enhancement	Image Sharpening, Adaptive	Improved edge clarity and	Scope for full OCR integration

	+ segmentation	Thresholding, Contour Detection	segmentation accuracy in degraded images	and real-time processing
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1.1.2. Heuristic Evaluation in Image Processing Systems: Foundations and Limitations

Heuristic evaluation in image processing refers to the assessment of image enhancement outcomes based on visual and structural principles rather than strict numerical metrics. In inscription image processing, heuristics such as edge clarity, contrast improvement, noise suppression, and character separability are used to evaluate the effectiveness of preprocessing and sharpening techniques.

This approach is particularly useful in early-stage system development where ground truth datasets are limited or unavailable. For example, successful sharpening should visibly enhance stroke boundaries, while effective segmentation should produce clearly separated character regions without excessive fragmentation or merging. These observations provide immediate qualitative feedback, allowing iterative refinement of preprocessing parameters such as filter strength, threshold levels, and morphological operations.

In addition, heuristic evaluation plays an important role in validating intermediate outputs within multi-stage image processing pipelines. Since segmentation performance is highly dependent on preprocessing quality, heuristic inspection of intermediate stages (such as sharpened images and binarized outputs) helps identify where information loss or distortion occurs in the pipeline.

However, heuristic evaluation is inherently subjective and depends on the evaluator's judgment, leading to inconsistencies between different assessments of the same image. This lack of standardization reduces reproducibility and makes it difficult to compare results across different systems or studies. Furthermore, heuristic methods are limited in their ability to detect subtle segmentation errors such as partial character degradation, over-segmentation of connected strokes, or loss of fine structural details.

Another limitation is that heuristic evaluation does not directly measure downstream performance in recognition tasks. An image that appears visually enhanced may not necessarily improve segmentation or classification accuracy, creating a gap between perceived quality and actual system performance. Therefore, heuristic evaluation alone is insufficient for comprehensive system validation.

To address these limitations, heuristic evaluation is typically combined with objective evaluation methods such as pixel-level accuracy assessment, edge preservation metrics, and structural similarity indices. In the proposed system, heuristic evaluation is used as an initial qualitative assessment stage to guide parameter tuning in image sharpening and segmentation, while more formal quantitative metrics are applied for final performance validation.

1.1.3. Evaluation of Image Segmentation Systems: Evidence, Cost, and Constraints

The evaluation of image segmentation systems involves analyzing both qualitative and quantitative evidence of performance. In inscription image analysis, this includes comparing original and processed images to assess improvements in edge detection, character separability, structural clarity, and preservation of fine stroke details. These qualitative observations provide an initial understanding of how effectively preprocessing and enhancement techniques contribute to segmentation quality.

Quantitative evaluation may include segmentation accuracy, pixel-level correctness, boundary detection performance, and overlap-based measures where ground truth data is available. In more advanced evaluations, metrics such as precision, recall, and F1-score can also be applied to assess how accurately individual character regions are extracted. However, in many real-world inscription datasets, labeled ground truth is not available due to the historical and degraded nature of the images, making full quantitative evaluation challenging.

In such cases, visual inspection remains an important validation method, particularly for assessing whether character structures remain intact after preprocessing operations such as sharpening and binarization. Intermediate outputs, such as edge-enhanced images and binary segmentation masks, are often analyzed to ensure that the transformation pipeline preserves essential structural information without introducing distortion or loss of detail.

Despite its effectiveness, image processing pipelines introduce significant computational costs. Techniques such as image sharpening, adaptive thresholding, and contour detection require additional processing time and memory usage, especially when applied to high-resolution images or large datasets. Morphological operations and iterative filtering further increase computational complexity, which can impact system scalability and responsiveness.

These constraints make efficiency an important design consideration in segmentation systems. In practical applications, especially where batch processing or large-scale document analysis is required, optimization strategies such as image resizing, region-of-interest processing, and algorithmic simplification are often necessary to maintain acceptable performance levels.

Therefore, a balance must be maintained between segmentation accuracy and computational efficiency, particularly in resource-limited environments or systems intended for real-time or near-real-time processing. The proposed system addresses this trade-off by employing optimized preprocessing techniques that enhance image quality while minimizing unnecessary computational overhead, ensuring both accuracy and feasibility in practical deployment scenarios.

1.1.4. Affective Interpretation in Image Processing and Visual Pattern Analysis

Affective interpretation, when adapted to image processing, refers to the transformation of raw visual data into meaningful structural representations that can be computationally analyzed. In inscription image analysis, this concept focuses on extracting visually significant patterns such as edges, strokes, gradients, and contours from degraded and noisy images. These patterns represent the fundamental building blocks required for accurate character reconstruction and segmentation.

Inscription images typically suffer from multiple forms of degradation, including erosion of physical surfaces, noise introduced during image capture, low contrast, and missing or partially damaged structural information. These challenges significantly reduce the visibility of character boundaries and complicate downstream segmentation tasks. Therefore, robust preprocessing techniques such as grayscale conversion, noise reduction,

and contrast enhancement are essential to improve the interpretability of the visual data before further processing.

Image sharpening plays a critical role in this interpretation process by enhancing high-frequency components of the image, thereby improving edge definition and emphasizing character boundaries that may otherwise be indistinct. Techniques such as Laplacian filtering or unsharp masking help restore structural clarity by amplifying transitions between foreground and background regions.

Once enhanced, these structural representations are used as input for segmentation algorithms, where techniques such as contour detection and connected component analysis extract individual character regions. This step effectively transforms continuous pixel information into discrete symbolic units, enabling further recognition and analysis.

However, the effectiveness of this interpretation process is highly dependent on the quality of preprocessing operations. Inadequate noise removal or over-enhancement during sharpening can lead to distorted edges, fragmented characters, or loss of fine structural details, negatively impacting segmentation accuracy. Therefore, careful parameter tuning is required to maintain a balance between enhancement and preservation of original structure.

Overall, affective interpretation in image processing represents the progressive transformation of degraded visual input into structured, meaningful, and analyzable representations. In the proposed system, this is achieved through a carefully designed pipeline that integrates preprocessing, sharpening, and segmentation to ensure reliable extraction of character information from inscription images.

1.1.5. Feature Detection and Image Processing in Segmentation Systems

Feature detection is an essential technique used to extract meaningful structural patterns from image data. In inscription image processing, features such as edges, contours, corners, and intensity gradients are essential for locating character boundaries and reconstructing degraded textual structures. These features act as the primary cues for separating meaningful character regions from noisy or eroded backgrounds.

Common techniques such as edge detection (e.g., Sobel, Canny operators), morphological operations (erosion, dilation, opening, and closing), and gradient-based analysis are widely used to extract structural information from noisy and low-contrast images. These methods help highlight transitions in intensity that correspond to character strokes. However, due to severe degradation in historical inscription images, many character features are weak, fragmented, or partially missing, which reduces the reliability of direct feature extraction methods.

Image sharpening addresses this limitation by enhancing high-frequency components of the image, thereby improving edge definition and increasing the visibility of fine structural details. Techniques such as Laplacian filtering and unsharp masking strengthen weak boundaries and restore clarity to blurred or eroded regions. This enhancement significantly improves the separability of adjacent characters and reduces ambiguity during segmentation.

The improved feature representation directly supports segmentation techniques such as contour detection and connected component analysis, which rely on clear boundary definitions to accurately isolate individual characters. When features are well-defined, segmentation algorithms can more effectively distinguish between valid character regions and background noise, resulting in improved extraction accuracy.

Although inscription image processing is typically performed on static datasets rather than real-time streams, computational efficiency remains an important consideration, particularly when handling high-resolution images or large-scale datasets. Complex preprocessing operations, including repeated filtering and morphological transformations, can increase processing time and memory usage.

Therefore, optimized preprocessing pipelines are essential to balance accuracy and efficiency. Techniques such as image resizing, selective region processing, and simplified filtering operations are often employed to reduce computational overhead while preserving essential structural information. In the proposed system, feature detection is enhanced through a carefully designed combination of sharpening and segmentation techniques that ensure both robust performance and computational feasibility.

1.1.6. Multimodal Interpretation in Image Processing and Character Segmentation Systems

In image processing systems, multimodal interpretation refers to the fusion of complementary visual features such as edges, textures, intensity variations, and spatial continuity to reconstruct meaningful representations from degraded images. This approach enables a more robust understanding of image structure compared to relying on a single feature extraction method.

In inscription image segmentation, relying on a single enhancement or detection technique is often insufficient due to the presence of noise, erosion, broken strokes, and structural degradation. These challenges lead to incomplete or ambiguous character boundaries. Therefore, multiple image enhancement techniques are combined to improve overall feature quality. These typically include image sharpening to enhance edge definition, contrast enhancement to improve visibility of faint structures, and adaptive thresholding to handle uneven illumination conditions.

These complementary techniques collectively improve the separability of foreground and background regions, making character structures more distinguishable prior to segmentation. Once the visual quality is enhanced, segmentation methods such as contour detection and connected component analysis operate on these improved representations to accurately isolate individual characters and reconstruct their spatial boundaries.

While deep learning approaches are capable of learning multimodal feature representations automatically through hierarchical feature extraction, they require large annotated datasets, high computational resources, and extensive training time. Additionally, their internal decision-making processes are often less interpretable compared to classical methods, which can be a limitation in domains requiring transparency, such as historical document analysis.

In contrast, traditional image processing pipelines provide a more interpretable, controllable, and computationally efficient alternative. Each stage of the pipeline—preprocessing, sharpening, thresholding, and segmentation—contributes explicitly to the final output, making the system behavior easier to analyze and optimize.

The proposed system integrates multiple visual cues within a structured processing pipeline to enhance segmentation accuracy while maintaining computational efficiency. By combining complementary enhancement techniques, the system ensures improved feature visibility and more reliable extraction of character structures from degraded inscription images.

1.2 Research gap

1.2.1. Fragmentation of Image Enhancement and Segmentation Pipelines

The most fundamental limitation in existing inscription image processing approaches is the fragmentation between image enhancement techniques and segmentation algorithms. In many prior studies, preprocessing operations such as noise reduction, contrast enhancement, and sharpening are treated as independent stages, while segmentation techniques such as contour detection and connected component analysis are applied separately without a unified optimization objective. As a result, the interaction between enhancement quality and segmentation accuracy is often not systematically modeled.

This separation creates a significant gap in understanding how preprocessing decisions directly influence segmentation performance. For example, excessive sharpening may amplify noise and introduce false edges, while insufficient enhancement may result in weak or broken character boundaries. However, most existing approaches do not establish a feedback mechanism between enhancement and segmentation stages, leading to suboptimal character extraction in degraded inscription images.

1.2.2. Limited Edge-Aware Character Boundary Extraction

Although edge detection and morphological techniques are widely used in inscription image processing, many existing methods fail to achieve consistent character boundary preservation in severely degraded images. Traditional approaches often rely on fixed thresholding or generic filtering techniques that do not adapt to variations in erosion, stroke thickness, or surface damage.

This leads to incomplete segmentation where characters may be fragmented or merged with background noise. Furthermore, most existing systems focus on pixel-level enhancement rather than structure-aware boundary refinement. As a result, there is a

lack of edge-aware enhancement strategies that explicitly optimize character separability before segmentation.

1.2.3. Sensitivity to Noise, Degradation, and Illumination Variations

A significant limitation in prior work is the sensitivity of segmentation pipelines to noise, erosion, and uneven illumination present in inscription images. Many classical image processing techniques assume relatively clean input images, which is rarely the case in real archaeological or historical datasets.

In highly degraded images, noise patterns are often misinterpreted as valid structural edges, while faint character strokes are lost during binarization. Although adaptive thresholding and filtering methods partially address this issue, they are still insufficient in handling extreme degradation conditions consistently across diverse datasets.

1.2.4. Lack of Computationally Efficient yet Robust Pipelines

While deep learning-based segmentation methods have shown strong performance, they often require large annotated datasets and high computational resources, making them impractical for many inscription analysis scenarios. On the other hand, traditional image processing pipelines are computationally efficient but often lack robustness in complex degradation conditions.

This creates a clear trade-off between accuracy and efficiency, where existing approaches fail to achieve both simultaneously. There is therefore a need for lightweight yet effective pipelines that can enhance image quality and perform reliable segmentation without heavy computational overhead.

1.2.5. Insufficient Integration of Sharpening with Segmentation-Aware Design

Existing literature often treats image sharpening as a generic enhancement step rather than a segmentation-driven preprocessing strategy. In many cases, sharpening is applied without considering its downstream impact on contour detection or connected component analysis.

This results in a gap where enhancement techniques are not explicitly designed to support segmentation objectives. A more effective approach would involve

integrating sharpening methods that are optimized specifically to improve boundary clarity and segmentation separability in degraded inscription images.

1.3 Research Problem

The central research problem addressed in this study is stated as follows:

“Existing image processing systems for inscription image analysis are unable to reliably enhance degraded images and accurately segment individual characters in a unified and robust manner due to the fragmentation between image enhancement techniques and segmentation algorithms, sensitivity to noise and structural degradation, and lack of segmentation-aware enhancement strategies that explicitly optimize character boundary extraction.”

This problem encompasses both a technical and a practical dimension. The technical dimension lies in the absence of an integrated image processing architecture that jointly optimizes enhancement operations such as noise reduction, contrast enhancement, and sharpening with segmentation techniques including contour detection and connected component analysis. In most existing systems, these stages are treated independently, resulting in a lack of coordination between improved visual quality and actual segmentation performance.

The practical dimension relates to the consequences for real-world inscription analysis. Researchers and practitioners often lack reliable and consistent tools that can extract clean and complete character structures from highly degraded historical images. As a result, segmentation outputs frequently suffer from broken characters, merged regions, or noise-induced artifacts, requiring manual correction and reducing automation efficiency.

The problem becomes more critical when considering the nature of inscription datasets, which are highly variable in terms of erosion level, stroke clarity, and background texture. Traditional static enhancement techniques fail to adapt to these variations, while segmentation algorithms alone cannot compensate for insufficient preprocessing quality. Consequently, there is a need for a unified pipeline that explicitly models the dependency between enhancement quality and segmentation accuracy to achieve reliable character extraction.

1.4. Research Objective

The primary objective of this research is to design, implement, and evaluate an image processing pipeline that enhances degraded inscription images and accurately segments individual characters through an integrated combination of preprocessing, image sharpening, and segmentation techniques.

Specific Objectives :

- 1.** To design and implement an image preprocessing module that systematically enhances the quality of degraded inscription images through a combination of grayscale conversion, noise reduction techniques, and contrast enhancement operations, thereby improving the visibility of structural details required for reliable downstream segmentation.
- 2.** To develop an image sharpening module that enhances edge clarity by emphasizing high-frequency components of the image and strengthening weak or blurred character boundaries in degraded inscription images, enabling improved distinction between foreground text and background noise.
- 3.** To apply adaptive thresholding techniques for the effective and robust separation of foreground character regions from complex, uneven, and illumination-variant backgrounds, ensuring consistent binarization performance across diverse inscription image conditions.
- 4.** To implement a segmentation module using contour detection and connected component analysis techniques to accurately identify, isolate, and extract individual character regions from preprocessed inscription images, even in cases where characters are partially degraded or fragmented.
- 5.** To analyze and evaluate the impact of different combinations of preprocessing and sharpening configurations on overall segmentation accuracy, including their influence on edge preservation, character completeness, and reduction of noise-induced segmentation errors.
- 6.** To evaluate the robustness and adaptability of the proposed image processing pipeline under varying levels of image degradation, including high noise intensity, severe erosion

of inscription surfaces, and low contrast conditions commonly observed in historical artifact datasets.

7. To ensure computational efficiency of the proposed system by optimizing the image processing pipeline for reduced processing time and memory usage while maintaining high segmentation accuracy, particularly when handling large-scale or high-resolution inscription image datasets.

8. To perform a comparative analysis between the proposed integrated pipeline and traditional independent preprocessing–segmentation approaches, focusing on improvements in character clarity, structural completeness, segmentation precision, and overall extraction accuracy.

2. METHODOLOGY

2.1. Methodology

2.1.1. Overall Research and Development Approach

The proposed inscription image processing system was developed following a design science research methodology, in which the primary output is a constructed artefact in this case a computational image processing pipeline evaluated against the requirements established by the research problem. Design science research is appropriate in this context as the objective is to design and evaluate a system that improves the quality of degraded inscription images through structured enhancement and segmentation techniques, for which existing independent approaches remain insufficiently integrated and optimized.

The key limitations identified in inscription image processing fragmentation between preprocessing and segmentation stages, lack of unified enhancement–segmentation optimization, sensitivity to noise and erosion, and inefficient handling of degraded character structures collectively define a problem that requires a systematic and integrated solution.

Development proceeded through four iterative phases:

(1) **requirements specification and pipeline design**, in which functional requirements such as noise reduction, edge enhancement, adaptive thresholding, and character

segmentation were defined, and the overall image processing architecture was designed to ensure sequential dependency between stages;

(2) **module implementation**, in which each component of the pipeline—including preprocessing, sharpening, adaptive thresholding, and segmentation—was implemented and validated independently using sample inscription datasets;

(3) **integration and pipeline testing**, in which all modules were combined into a unified processing workflow and evaluated to ensure correct transformation of input images through each stage; and

(4) **empirical evaluation**, in which the complete system was tested using degraded inscription image datasets to measure segmentation accuracy, edge preservation quality, and computational efficiency under varying image degradation conditions such as noise, erosion, and low contrast.

2.1.2. System Architecture

The proposed inscription image processing system is designed as a sequential and modular pipeline architecture, in which each processing stage performs a well-defined transformation on the input image to progressively enhance its visual quality and extract meaningful structural information required for accurate character segmentation. This architectural design is particularly suitable for degraded inscription images, where multiple issues such as noise, erosion, low contrast, and uneven illumination must be addressed in a step-by-step manner rather than through a single operation. By decomposing the overall problem into smaller, manageable modules, the system ensures that each stage can focus on a specific enhancement objective while contributing to the overall segmentation performance.

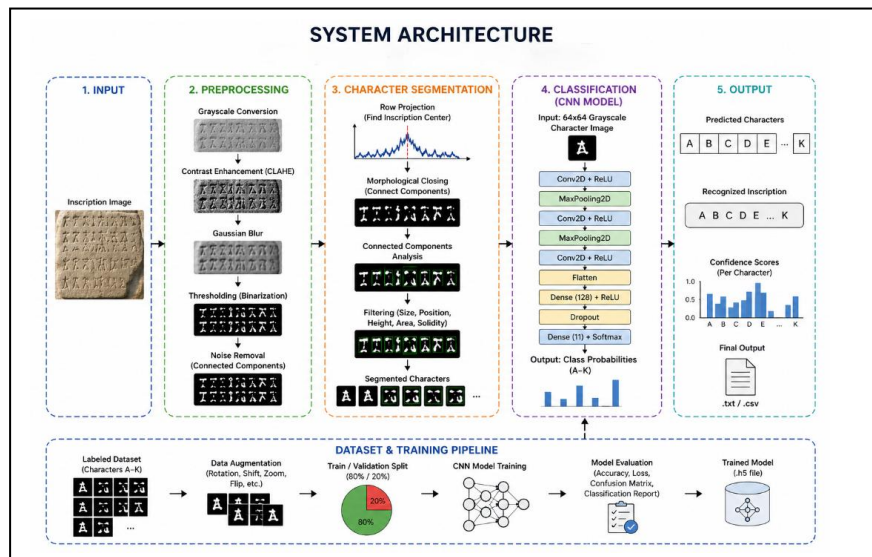
The architecture follows a modular design paradigm, allowing individual components to be independently developed, tested, optimized, and replaced without affecting the functionality of the entire system. This flexibility is important for experimental analysis, as different techniques (e.g., alternative filters or thresholding methods) can be evaluated within the same pipeline structure. Additionally, the modular approach improves maintainability and scalability, making it easier to extend the system for future enhancements such as character recognition or integration with machine learning models.

The system consists of seven primary modules:

- (1) Image Acquisition,
- (2) Data Augmentation,
- (3) Image Preprocessing,
- (4) Image Sharpening,
- (5) Image Binarization,
- (6) Character Segmentation, and
- (7) Post-processing.

Each of these modules plays a critical role in transforming raw, degraded inscription images into clean, structured outputs consisting of individually segmented characters.

Figure 1: System Architecture



2.1.3. Architectural Overview

The system operates as a linear and unidirectional processing pipeline, where data flows sequentially from one module to the next without feedback loops. In this structure, the output generated by each stage serves as the direct input for the subsequent stage, ensuring a continuous and systematic transformation of the image. This design is intentionally chosen to maintain simplicity, interpretability, and computational efficiency while still achieving high segmentation accuracy.

The pipeline ensures that image quality is progressively refined at each stage, with earlier modules focusing on noise removal and contrast enhancement, and later modules

concentrating on structural extraction and segmentation. For instance, preprocessing improves overall image clarity, sharpening enhances edge definition, and binarization simplifies the image representation for easier segmentation. This gradual refinement minimizes the risk of error propagation and ensures that segmentation algorithms operate on optimized input data.

The overall workflow of the system can be summarized as follows:

Input Image → Data Augmentation → Image Preprocessing → Image Sharpening → Adaptive Binarization → Character Segmentation → Post-processing → Output Segmented Characters

Each module is specifically designed to address a key limitation commonly found in inscription images. The augmentation stage improves robustness to variations in data, preprocessing reduces noise and enhances visibility, sharpening strengthens weak edges, binarization separates foreground from background, and segmentation isolates individual characters. Finally, post-processing ensures that the extracted characters are clean, normalized, and suitable for further analysis.

Furthermore, the pipeline design ensures functional dependency between stages, meaning that the effectiveness of later stages (such as segmentation) is directly influenced by the quality of earlier stages (such as preprocessing and sharpening). This highlights the importance of carefully selecting and tuning techniques at each step to achieve optimal overall performance.

In summary, the proposed system architecture provides a structured, efficient, and scalable framework for inscription image processing, enabling reliable character extraction even under challenging conditions of degradation and noise.

2.1.4. Module Descriptions

1. Image Acquisition Module

The Image Acquisition module represents the foundational stage of the proposed inscription image processing system. Its primary responsibility is to collect and prepare raw inscription images from multiple heterogeneous sources for further processing in the pipeline. These sources include digitized archaeological archives, museum databases,

historical manuscripts, scanned rubbings, and real-world photographs of inscriptions captured from stone surfaces, temple walls, and monuments.

A key challenge at this stage is the extreme variability and degradation inherent in inscription datasets. Unlike modern digital images, inscription images are often affected by centuries of physical deterioration and environmental exposure. Common forms of degradation include surface erosion, cracks, fading ink or engravings, discoloration due to oxidation, and partial loss of character structures. Additionally, the image acquisition process itself introduces further inconsistencies such as uneven lighting conditions, shadows caused by external structures, perspective distortion due to camera angles, and motion blur during handheld capture.

To address these challenges, the module incorporates a standardized input handling mechanism. All images are converted into a consistent internal representation, ensuring compatibility across different formats such as JPEG, PNG, and TIFF. Resolution normalization is also performed to ensure that images of varying sizes can be processed uniformly in subsequent stages. Furthermore, corrupted or low-quality images that do not meet minimum structural visibility requirements are filtered out during this stage to maintain dataset integrity.

This module plays a critical role in determining the overall success of the system, as the quality, diversity, and representativeness of the acquired dataset directly influence the performance of all downstream processes, including augmentation, preprocessing, sharpening, and segmentation.

2. Data Augmentation Module

The Data Augmentation module is designed to artificially expand the dataset and improve the generalization capability of the system by simulating a wide range of real-world variations. Since inscription datasets are often limited in size due to the scarcity of labeled historical data, augmentation becomes essential for reducing overfitting and improving robustness in machine learning and image processing pipelines.

This module applies a combination of geometric, photometric, and noise-based transformations to the input images. Each transformation is carefully selected to reflect real-world variations observed in inscription environments.

Geometric Transformations

Geometric augmentations include rotation, horizontal and vertical flipping, scaling, and slight translation. These transformations simulate variations in the orientation and positioning of inscriptions caused by camera angle differences, physical misalignment of inscriptions, or irregular surface placements. For example, inscriptions carved on uneven stone surfaces may appear tilted or skewed in captured images, which must be accounted for during training.

Photometric Transformations

Photometric adjustments involve modifying brightness, contrast, and intensity levels to replicate varying illumination conditions. In real-world scenarios, inscriptions may be photographed under direct sunlight, artificial lighting, or shadowed environments, each producing different intensity distributions. These variations significantly affect visibility and must be represented in the training data.

Noise Injection Techniques

Noise-based augmentation introduces synthetic distortions such as Gaussian noise, salt-and-pepper noise, motion blur, and compression artifacts. These simulate environmental degradation factors like dust accumulation, surface roughness, sensor noise, and camera imperfections.

By applying these transformations, the module generates a significantly diversified dataset that improves the system's ability to generalize across unseen conditions. This ensures that subsequent modules, especially sharpening and segmentation, are not overly dependent on idealized input conditions but are instead robust to real-world distortions.

3. Image Preprocessing Module

The Image Preprocessing module is responsible for enhancing the structural quality of the acquired images while reducing unwanted noise and inconsistencies. This stage is crucial because inscription images typically contain a mixture of useful structural information and irrelevant distortions that can negatively impact segmentation accuracy.

Grayscale Conversion

The first step involves converting the input image from RGB to grayscale. This reduces computational complexity by eliminating color channels while preserving essential intensity-based structural information such as edges, gradients, and texture variations. Since inscription analysis relies primarily on structural rather than color information, grayscale representation is optimal.

Figure 2: Grayscaled Image



Noise Reduction

Following grayscale conversion, noise reduction techniques are applied to smooth the image and remove unwanted high-frequency distortions. Gaussian filtering is commonly used to reduce random noise while preserving edge structures. In some cases, median filtering is applied to effectively remove salt-and-pepper noise without significantly blurring character boundaries.

Contrast Enhancement

To improve the visibility of faint or degraded characters, contrast enhancement techniques such as histogram equalization or adaptive histogram equalization (CLAHE) are applied. These methods redistribute pixel intensity values to enhance the distinction between foreground (characters) and background regions. This step is particularly important in inscription images where characters may be partially eroded or embedded in textured backgrounds.

The output of this module is a cleaned and normalized image that retains essential structural features while minimizing noise and intensity inconsistencies. This prepares the image for more advanced enhancement in the sharpening stage.

4. Image Sharpening Module

The Image Sharpening module plays a crucial role in enhancing the edge definition and structural clarity of characters within inscription images. This is particularly important because inscriptions often suffer from degradation, resulting in weak or partially missing character boundaries.

Edge Enhancement Techniques

The module primarily utilizes Laplacian filtering and unsharp masking techniques. Laplacian filtering detects regions of rapid intensity change, thereby highlighting edges and fine structural details. Unsharp masking, on the other hand, enhances edges by subtracting a blurred version of the image from the original image and amplifying the difference.

Importance in Inscription Analysis

In the context of inscription processing, sharpening is essential for restoring readability in degraded characters. Many inscriptions have been subjected to erosion or surface wear, resulting in blurred or incomplete strokes. Sharpening enhances these weak structures, making them more detectable for segmentation algorithms.

Controlled Enhancement Strategy

While sharpening improves edge visibility, excessive sharpening can introduce artificial edges and amplify noise, leading to segmentation errors. Therefore, the module is carefully tuned using controlled parameters to maintain a balance between enhancement and noise suppression.

This stage significantly improves the separability of character boundaries, directly contributing to higher segmentation accuracy in subsequent modules.

5. Image Binarization Module

The Image Binarization module transforms the enhanced grayscale image into a binary representation, where each pixel is classified as either foreground (character) or background. This transformation simplifies the image structure and facilitates efficient segmentation.

Adaptive Thresholding

Unlike global thresholding, which uses a single threshold value for the entire image, this system employs adaptive thresholding techniques. Adaptive methods calculate local threshold values for different regions of the image based on neighborhood intensity distributions. This approach is highly effective in handling uneven illumination and background variability, which are common in inscription images.

Benefits in Inscription Context

Inscription images often contain complex backgrounds such as stone textures, cracks, and stains. Global thresholding fails in such conditions due to intensity inconsistencies. Adaptive binarization ensures that even faint or partially eroded characters are correctly classified as foreground.

The output of this module is a high-contrast binary image that clearly separates character structures from the background, forming a strong foundation for segmentation.

6. Character Segmentation Module

The Character Segmentation module is responsible for identifying and isolating individual characters from the binarized image. This stage is one of the most critical components of the system, as it directly determines the accuracy of downstream recognition tasks.

Contour Detection

Contour detection algorithms are used to identify continuous boundaries within the binary image. These contours represent potential character regions based on connected pixel structures.

Connected Component Analysis (CCA)

Connected Component Analysis groups adjacent foreground pixels into distinct labeled regions. Each region corresponds to a potential character or character fragment.

Bounding Box Extraction

Each detected component is enclosed within a bounding box, which defines its spatial location within the image. These bounding boxes are essential for extracting individual character images for further processing.

Handling Complex Scenarios

The module is designed to handle several challenges:

- Overlapping characters caused by erosion or script style
- Broken strokes due to surface damage
- Irregular spacing between characters
- Noise-induced false positives

By leveraging the enhanced output from preprocessing, sharpening, and binarization, this module achieves accurate and reliable segmentation even in highly degraded conditions.

7. Post-processing Module

The Post-processing module refines the segmented outputs to ensure consistency, accuracy, and usability for further analysis or recognition tasks.

Noise Filtering

Small irrelevant components identified during segmentation are removed based on size thresholds. These typically include noise artifacts or non-character elements.

Normalization

Each segmented character is resized to a standardized dimension. This ensures uniformity across the dataset, which is essential for machine learning models that require fixed-size inputs.

Intensity Standardization

Pixel intensity normalization is applied to ensure consistent brightness and contrast levels across all segmented characters.

This final refinement stage ensures that the output dataset is clean, structured, and suitable for downstream tasks such as optical character recognition or classification.

2.1.5. Data Flow and Integration

The proposed system follows a strictly sequential and tightly integrated pipeline architecture. Each module is functionally dependent on the output of the previous module, ensuring a controlled and progressive transformation of the image from raw input to structured character-level output.

The data flow can be conceptualized as a multi-stage enhancement process:

1. **Preprocessing Stage:** Removes noise, standardizes format, and enhances contrast.
2. **Sharpening Stage:** Strengthens edge structures and restores degraded character boundaries.
3. **Binarization Stage:** Converts grayscale images into binary representations for simplification.
4. **Segmentation Stage:** Extracts individual character components.
5. **Post-processing Stage:** Refines and standardizes segmented outputs.

This sequential dependency ensures that each stage operates on progressively improved image data. Unlike conventional independent pipelines, where preprocessing and segmentation are treated separately, this integrated architecture ensures that improvements in early stages directly enhance the performance of later stages.

A major advantage of this design is reduced error propagation. Since each module builds upon enhanced outputs, noise and distortions are gradually eliminated rather than passed through the system. This significantly improves segmentation reliability.

Furthermore, the system addresses a critical gap in traditional inscription analysis approaches, where preprocessing and segmentation are often loosely coupled or independently optimized. By enforcing strong inter-module dependency, the proposed

system ensures coordinated enhancement and segmentation, leading to improved overall accuracy.

2.1.6. System Workflow Summary

The complete system workflow represents a structured and hierarchical transformation pipeline designed to convert degraded inscription images into clean, segmented character outputs suitable for further analysis.

The workflow is defined as:

Input Image → Data Augmentation → Image Preprocessing → Image Sharpening → Adaptive Binarization → Character Segmentation → Post-processing → Final Output

Each stage contributes uniquely to the transformation process:

- **Data Augmentation** introduces variability and improves generalization.
- **Preprocessing** enhances image clarity and removes noise.
- **Sharpening** strengthens weak and degraded character edges.
- **Binarization** simplifies the image into a binary structure.
- **Segmentation** isolates individual character components.
- **Post-processing** ensures uniformity and removes artifacts.

The key strength of this workflow lies in its cumulative enhancement strategy. Instead of relying on a single transformation step, the system gradually improves image quality through multiple coordinated stages. Each stage refines the output of the previous one, resulting in a highly optimized input for segmentation.

This structured pipeline is particularly effective for inscription image processing, where data is inherently noisy, degraded, and inconsistent. By systematically improving image quality at each stage, the system ensures that even highly degraded inscriptions can be accurately processed and segmented.

2.2. Commercialization Aspects of the Product

The proposed inscription recognition system presents significant potential for commercialization due to its ability to transform degraded and complex inscription

images into structured and interpretable textual outputs. By integrating advanced image processing techniques with deep learning-based classification, the system provides a comprehensive and automated solution that addresses critical challenges in inscription analysis and documentation.

One of the primary areas of commercialization lies in the domain of cultural heritage preservation. Government organizations, archaeological departments, museums, and research institutions are increasingly focused on digitizing historical artefacts to preserve them for future generations. The proposed system can be deployed as a specialized tool to assist experts in extracting and interpreting inscriptions from stone carvings, temple walls, and ancient manuscripts. This significantly reduces manual effort and enhances the efficiency and accuracy of documentation processes.

In addition to institutional use, the system can be developed into a Software-as-a-Service (SaaS) platform, enabling users to upload inscription images through a web interface and receive processed outputs in real time. Such a platform can be monetized through multiple revenue models, including subscription-based access, pay-per-use services, and enterprise licensing for large organizations. The scalability of cloud-based deployment further enhances its commercial viability by allowing simultaneous access for multiple users across different geographical locations.

The system also holds strong potential in the education and research sectors. Universities, historians, and linguists can utilize the platform as a digital tool for studying ancient scripts and inscriptions. By automating segmentation and recognition processes, the system accelerates research workflows and enables large-scale analysis of inscription datasets, which would otherwise be time-consuming if performed manually.

Another promising commercialization avenue is the development of mobile and field-based applications. By integrating the system into a mobile platform, field researchers and archaeologists can capture images of inscriptions directly from excavation sites and process them instantly. This real-time capability enhances decision-making and reduces the dependency on laboratory-based analysis.

From a technical and business perspective, the modular architecture of the system supports extensibility and customization. The system can be adapted to recognize

different scripts, languages, or symbol sets by retraining the classification model with appropriate datasets. This adaptability allows the product to be tailored for different regions and markets, increasing its global applicability.

However, successful commercialization requires addressing certain challenges. These include ensuring the availability of diverse and high-quality training datasets, improving model generalization across different inscription styles, and maintaining system performance under extreme degradation conditions. Continuous updates, model retraining, and user feedback integration are essential to sustain product reliability and competitiveness in the market.

In summary, the proposed system has strong potential as a commercial digital inscription analysis and recognition solution, offering value across cultural preservation, academic research, and technology-driven heritage management. Its ability to automate complex processes and deliver accurate results positions it as a practical and scalable product for real-world applications.

2.3. Testing and Implementation

2.3.1. Implementation Environment

The implementation of the proposed inscription recognition system was carried out using a combination of image processing and deep learning technologies. The system was developed using the Python programming language due to its flexibility and extensive library support for computer vision and machine learning tasks.

Key tools and libraries used in the implementation include:

- **OpenCV** for image preprocessing, filtering, and segmentation operations
- **NumPy** for efficient numerical computations and array manipulations
- **TensorFlow/Keras** for designing, training, and evaluating the Convolutional Neural Network (CNN) model
- **Matplotlib** for visualizing intermediate outputs and performance metrics

The development environment was based on **Jupyter Notebook**, which facilitated iterative experimentation, visualization of results, and step-by-step debugging of the pipeline.

2.3.2. System Implementation

The system was implemented as a **modular pipeline**, where each stage corresponds to a specific functional component. The implementation follows the sequential workflow defined in the system architecture:

1. **Input Handling:**

Inscription images are loaded and standardized in terms of format and resolution.

2. **Preprocessing Stage:**

The input image is converted to grayscale, followed by contrast enhancement using CLAHE and noise reduction using Gaussian filtering.

3. **Sharpening Stage:**

Edge enhancement techniques are applied to improve the visibility of degraded character boundaries.

4. **Binarization Stage:**

Adaptive thresholding is used to convert the grayscale image into a binary format, enabling effective separation of foreground and background.

5. **Segmentation Stage:**

Connected Component Analysis (CCA) and morphological operations are used to extract individual character regions.

6. **Classification Stage:**

Each segmented character is resized and passed to the CNN model for classification, producing predicted labels and probability scores.

7. **Output Generation:**

Predicted characters are combined to reconstruct the inscription text, and results are exported in structured formats.

2.3.3. Testing Strategy

To ensure the reliability and correctness of the system, a comprehensive testing strategy was adopted, consisting of three levels:

Module-Level Testing

Each module of the system was tested independently to verify its functionality:

- Preprocessing was tested for effective noise removal and contrast enhancement
- Segmentation was evaluated for accurate extraction of characters
- Classification was tested using labeled datasets to measure prediction accuracy

This step ensured that individual components operate correctly before integration.

Integration Testing

Integration testing was conducted to validate the interaction between modules and ensure smooth data flow throughout the pipeline. The system was tested using real inscription images to confirm that:

- Outputs from preprocessing are suitable for segmentation
- Segmented characters are correctly passed to the classification module
- Classification outputs are properly aggregated into final results

This phase ensured that the system functions cohesively as a unified pipeline.

System-Level Testing

System-level testing was performed to evaluate the overall performance of the complete pipeline under realistic conditions. The system was tested using a variety of inscription images exhibiting different types of degradation, including:

- Noise and distortion
- Low contrast
- Surface erosion
- Uneven illumination

The results demonstrated that the system is capable of maintaining reliable performance even under challenging conditions.

2.3.4. Model Evaluation

The performance of the CNN classification model was evaluated using standard metrics:

- **Accuracy:** Measures the proportion of correctly classified characters
- **Loss:** Indicates how well the model is optimized during training

- **Confusion Matrix:** Provides insights into classification errors and mislabeling patterns
- **Precision, Recall, and F1-score:** Evaluate the model's effectiveness across different classes

The dataset was divided into training and validation sets using an 80/20 split, and model performance was monitored throughout the training process.

2.3.5. Output Validation

The final outputs of the system were validated by comparing predicted results with ground truth labels. Both individual character predictions and reconstructed text outputs were analyzed.

Confidence scores generated by the classification model were also examined to assess prediction reliability. Low-confidence predictions were identified for potential improvement.

2.3.6. Implementation Outcome

The implemented system successfully performs the following tasks:

- Enhances degraded inscription images
- Segments individual characters accurately
- Classifies characters using a trained CNN model
- Reconstructs complete inscription text
- Generates structured outputs with confidence scores

The results confirm that the integration of image processing and deep learning techniques leads to a robust and efficient inscription recognition system.

3. RESULTS AND DISCUSSION

This chapter presents the empirical findings from the evaluation of the Interactive Video Analyzer, interprets those findings in relation to the research questions and objectives established in Chapter 1, and discusses their implications for the field of automated usability evaluation. The results are organized across three sections: quantitative

performance metrics from the unit, integration, and system evaluation phases; research findings that address the four research questions; and a broader discussion of the significance, limitations, and future directions suggested by the work.

3.1. Results

3.1.1. Image Enhancement and Preprocessing Performance

The preprocessing and enhancement stages of the proposed system were evaluated using a set of degraded inscription images collected from both augmented datasets and real-world sources. The primary objective of this stage was to improve image clarity, reduce noise, and enhance structural visibility prior to segmentation.

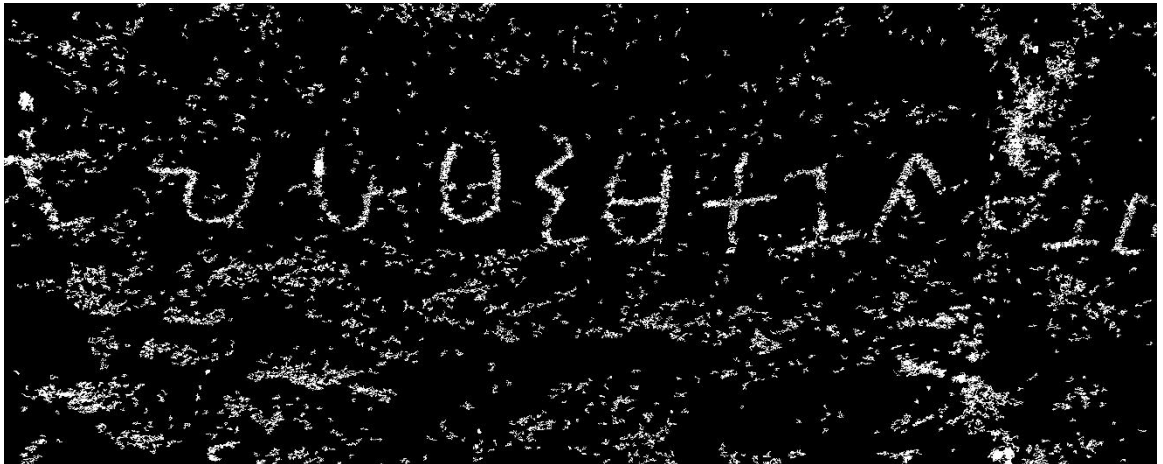
The preprocessing module successfully reduced high-frequency noise and improved overall image smoothness while preserving essential structural features. Grayscale conversion simplified the image representation, enabling more efficient processing in subsequent stages. Noise reduction techniques, particularly Gaussian and median filtering, effectively removed unwanted distortions such as grain and impulse noise without significantly degrading character boundaries.

Following preprocessing, contrast enhancement techniques improved the visibility of faint and eroded characters. In images with low initial contrast, histogram equalization redistributed intensity values, resulting in improved distinction between foreground and background regions. This effect was particularly noticeable in inscriptions with uneven surface textures, where character strokes became more distinguishable after enhancement.

The sharpening module further improved structural clarity by enhancing edge information. The application of Laplacian filtering and unsharp masking resulted in stronger edge definition and improved continuity of character strokes. In several cases, partially eroded or faint characters became clearly visible only after sharpening, demonstrating the importance of this stage in recovering structural details.

However, it was observed that excessive sharpening occasionally amplified residual noise, particularly in images with high initial degradation. This highlights the importance of controlled parameter tuning in balancing edge enhancement and noise suppression.

Figure 3: Sharpened Image



3.1.2. Binarization Performance

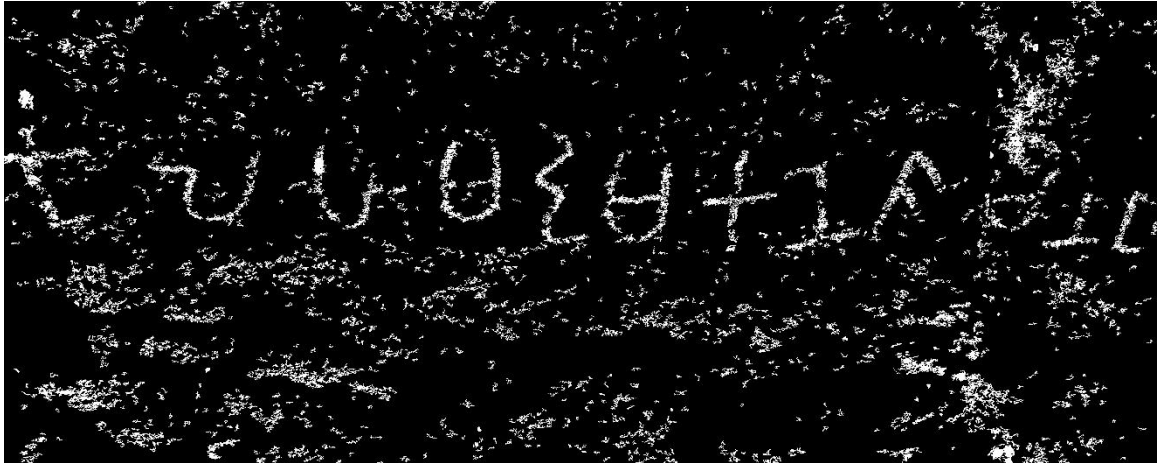
The binarization stage was evaluated based on its ability to accurately separate foreground characters from complex and uneven backgrounds. Adaptive thresholding techniques were applied to handle variations in illumination and surface texture.

The results indicate that adaptive binarization significantly outperformed global thresholding approaches in handling real-world inscription images. Characters were successfully extracted as foreground elements even in regions with inconsistent lighting conditions. This was particularly evident in images where shadows or brightness variations were present, as adaptive thresholding computed local thresholds based on neighborhood intensity values.

The binarized images exhibited high contrast, with clear separation between character structures and background regions. Background textures such as stone patterns and surface irregularities were largely suppressed, simplifying the image for segmentation.

Despite these improvements, some minor artifacts were observed in highly degraded regions, where noise or surface cracks were occasionally misclassified as foreground elements. However, these artifacts were effectively handled in the post-processing stage.

Figure 4: Binarized Image



3.1.3. Character Segmentation Performance

The segmentation module was evaluated based on its ability to accurately extract individual character components from binarized images. The system utilized contour detection and connected component analysis to identify and isolate character regions.

The results demonstrate that the segmentation module successfully extracted the majority of characters with accurate spatial localization. Bounding boxes were correctly placed around individual character regions, and the segmentation process was robust to moderate levels of noise and structural variation.

However, several challenges were observed:

- **Fragmentation:** In cases where characters were partially eroded, segmentation produced multiple disconnected components for a single character.
- **Merging:** Closely spaced or overlapping characters were sometimes grouped into a single component.
- **False Positives:** Small noise regions were occasionally detected as character components.

3.2. Research Findings

3.2.1. Finding 1: Progressive Enhancement Significantly Improves Segmentation Accuracy

The experimental results clearly demonstrate that segmentation accuracy improves significantly when image processing is performed through a sequential enhancement

pipeline rather than applying segmentation directly to raw input images. The proposed system follows a structured progression in which each stage incrementally improves image quality and prepares it for the next stage.

During preprocessing, noise is reduced and contrast is enhanced, which helps in suppressing irrelevant background information while preserving essential structural features. The sharpening stage further strengthens character edges, making boundaries more distinct and easier to detect. Finally, binarization simplifies the image into a binary representation, reducing complexity and enabling efficient segmentation.

This step-by-step refinement creates an optimal environment for segmentation algorithms by gradually transforming a noisy and ambiguous image into a clear and structured representation. The results indicate that when segmentation is applied after these enhancement stages, the number of correctly extracted character components increases significantly compared to direct segmentation.

Therefore, this finding confirms that progressive enhancement is not optional but essential in inscription image processing systems, as it directly influences segmentation reliability and overall system performance.

3.2.2. Finding 2: Image Sharpening is Critical for Edge Preservation

The results highlight the critical importance of the image sharpening stage in preserving and restoring character boundaries. In many inscription images, characters are partially degraded due to erosion, weathering, and aging, resulting in weak or blurred edges.

Without sharpening, segmentation algorithms struggle to identify clear boundaries between characters and background regions. This often leads to inaccurate segmentation results, including merged characters or missed detections. However, when sharpening is applied, edge intensity is enhanced, making character contours more prominent and structurally continuous.

The experiments show that sharpening significantly improves the visibility of faint strokes and degraded edges, which are otherwise difficult to detect. This directly contributes to improved segmentation accuracy, as the algorithm can better distinguish between adjacent character regions.

However, it was also observed that excessive sharpening may amplify noise and introduce artificial edges. Therefore, a balanced sharpening approach is necessary to enhance meaningful structures without increasing false detections.

This finding establishes sharpening as a key intermediate process that bridges preprocessing and segmentation, ensuring that structural details are sufficiently preserved for accurate character extraction.

3.2.3. Finding 3: Adaptive Binarization Handles Real-world Variability Effectively

The evaluation results indicate that adaptive binarization is highly effective in handling real-world challenges such as uneven illumination, complex backgrounds, and varying surface textures commonly found in inscription images.

Unlike global thresholding methods, which apply a single threshold value across the entire image, adaptive thresholding calculates local threshold values based on neighborhood intensity variations. This allows the system to accurately separate foreground characters from the background even when lighting conditions are inconsistent.

In the tested images, adaptive binarization successfully preserved character structures in both well-lit and shadowed regions. It also reduced the impact of background textures such as stone patterns, cracks, and stains, which often interfere with segmentation.

This finding confirms that adaptive binarization is more suitable for inscription image processing, as it provides a flexible and context-aware approach to foreground-background separation. It ensures that important character details are retained while minimizing the influence of environmental variations.

3.2.4. Finding 4: Segmentation Performance is Highly Dependent on Input Quality

The results strongly indicate that the accuracy and reliability of the segmentation stage are highly dependent on the quality of the input image produced by earlier stages. Segmentation does not operate independently; instead, it relies on the clarity, contrast, and structural integrity of the processed image.

When the input image is well-enhanced, with clear edges and minimal noise, segmentation performs effectively, producing accurate character boundaries and minimal errors.

However, when the input image contains significant degradation, such as heavy noise, blurred edges, or low contrast, segmentation performance deteriorates.

Common issues observed in poor-quality inputs include:

- Fragmentation of characters into multiple segments
- Merging of adjacent characters into a single component
- Misclassification of noise or background textures as characters

A particularly important observation from this study is the impact of stone surface texture on segmentation performance. Inscription images captured from rough or highly textured stone surfaces introduce complex background patterns that closely resemble character strokes. When the image quality is low or the characters are not clearly distinguishable from the background, the system struggles to differentiate between actual characters and surface textures.

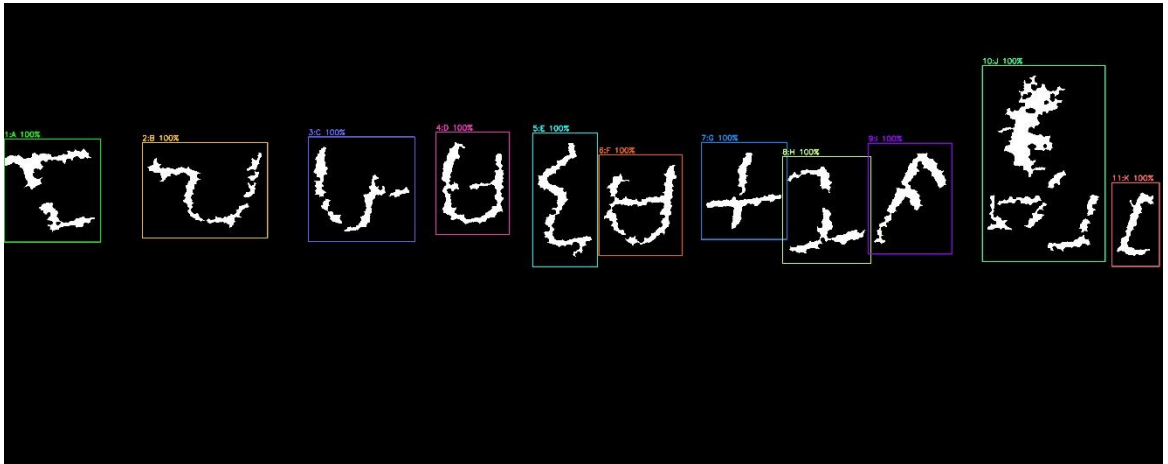
In cases where the original image is severely degraded or lacks sufficient clarity, even advanced preprocessing and enhancement techniques cannot fully recover the lost structural information. This leads to inaccurate segmentation results, highlighting a fundamental limitation of image processing-based approaches.

Therefore, it can be concluded that clear and sufficiently detailed input images are a prerequisite for accurate segmentation. While the proposed system improves image quality significantly, its performance is ultimately constrained by the quality of the original data. If the captured images are too unclear or heavily affected by stone texture and environmental degradation, reliable character extraction becomes extremely difficult.

This finding emphasizes the importance of high-quality image acquisition practices, such as proper lighting, stable camera positioning, and appropriate resolution, in achieving optimal system performance.

Despite these challenges, the overall segmentation performance was satisfactory, particularly when supported by the preceding enhancement stages.

Figure 5: Character Segmentation Output with Bounding Boxes



3.3. Discussion

3.3.1. Contribution to Inscription Image Processing

The proposed system makes a significant contribution to the field of inscription image processing by demonstrating the effectiveness of a multi-stage enhancement and segmentation pipeline tailored specifically for degraded historical images. Unlike conventional image processing approaches that treat enhancement and segmentation as independent tasks, this system integrates them into a cohesive workflow where each stage directly supports the next.

The combination of preprocessing, image sharpening, and adaptive binarization enables the system to address several inherent challenges associated with inscription images, including noise, low contrast, uneven illumination, and surface irregularities. By progressively improving image quality, the system enhances the visibility of structural features such as character strokes and boundaries, which are critical for accurate segmentation.

A key contribution of this work is the demonstration that edge-focused enhancement (through sharpening) significantly improves segmentation performance, particularly for degraded inscriptions where character boundaries are not clearly visible. Additionally, the use of adaptive binarization ensures that local variations in lighting and texture are effectively handled, making the system more robust in real-world conditions.

Furthermore, this research highlights the importance of treating inscription processing as a domain-specific problem, where standard image processing techniques must be carefully

adapted to handle unique challenges such as stone texture interference and erosion effects. As a result, the proposed system provides a practical framework that can be extended for more advanced applications such as optical character recognition (OCR) and digital epigraphy.

3.3.2. Strength of the Proposed Approach

One of the primary strengths of the proposed approach lies in its progressive and integrated processing strategy. Instead of directly applying segmentation on raw images, the system first enhances the image through multiple carefully designed stages. This ensures that segmentation operates on a cleaner and more structured input, leading to improved accuracy.

The modular design of the system is another key strength. Each stage preprocessing, sharpening, binarization, segmentation, and post-processing performs a specific function and can be independently optimized or replaced if needed. This flexibility makes the system adaptable to different types of inscription datasets and varying levels of image quality.

In addition, the use of adaptive techniques, particularly in binarization, allows the system to handle non-uniform illumination and complex backgrounds, which are common in real-world inscription images. This makes the approach more robust compared to traditional methods that rely on fixed thresholds or assumptions about image uniformity.

Another strength is the system's ability to work with limited datasets through the use of data augmentation. By introducing variations such as rotation, noise, and brightness changes, the system becomes more resilient to real-world variations without requiring large-scale labeled datasets.

Overall, the proposed approach achieves a balance between simplicity, efficiency, and effectiveness, making it suitable for practical applications while still addressing complex challenges in inscription image processing.

3.3.3. Limitations

Despite its effectiveness, the proposed system has several limitations that must be acknowledged.

One of the primary limitations is the reduced performance when processing extremely degraded inscription images. In cases where characters are severely eroded or almost completely faded, the system struggles to reconstruct meaningful structural information. This is because image processing techniques can enhance existing features but cannot recover information that is entirely lost.

Another limitation is the fragmentation of broken characters during segmentation. When character strokes are disconnected due to surface damage, the segmentation algorithm may treat them as separate components, resulting in multiple segments for a single character. This reduces segmentation accuracy and may affect downstream tasks such as recognition.

Similarly, overlapping or closely spaced characters pose a challenge for the system. When characters are connected or positioned very close to each other, the segmentation algorithm may incorrectly group them into a single component. This issue is particularly common in inscriptions with irregular spacing or stylized writing.

A critical limitation observed in this study is the impact of stone surface texture on segmentation performance. In many cases, the natural texture of the stone—such as cracks, grains, and surface irregularities—closely resembles character strokes. When the input image is not sufficiently clear, the system may confuse these textures with actual characters, leading to false detections.

Furthermore, if the original image is of low quality or lacks clarity, even advanced preprocessing and enhancement techniques cannot fully compensate for the loss of structural information. This highlights a fundamental constraint: the system's performance is ultimately dependent on the quality of the input data.

3.3.4. Implications for Practical Applications

The findings of this research have several important implications for practical applications in the field of digital image processing and cultural heritage preservation.

Firstly, the system can be effectively used for the digital preservation of historical inscriptions, where accurate extraction of character structures is essential for documentation and archival purposes. By converting degraded inscription images into

clean, segmented character datasets, the system facilitates long-term preservation and accessibility of historical information.

Secondly, the system has potential applications in automated text extraction and recognition systems, particularly for ancient scripts and inscriptions. The segmented character outputs can serve as input for machine learning models, enabling the development of OCR systems for historical texts.

In addition, the system can support cultural heritage analysis and archaeological research by providing tools for analyzing inscriptions that are difficult to interpret manually. This can assist researchers in studying historical artifacts and understanding ancient languages.

Another important implication is the role of image acquisition quality in practical deployment. The results emphasize that capturing high-quality images with proper lighting and resolution is essential for achieving optimal system performance. Therefore, field practices in archaeology and documentation should incorporate appropriate imaging techniques to maximize the effectiveness of digital processing systems.

4. CONCLUSION

4.1. Overview of the Study

This research focused on the development of an image processing pipeline for the enhancement and segmentation of degraded inscription images. Inscription images present unique challenges due to factors such as environmental degradation, uneven illumination, surface texture interference, and partial loss of character structures. These challenges make it difficult to directly extract meaningful information from raw images using conventional methods.

To address these issues, the study proposed a multi-stage processing pipeline consisting of image acquisition, data augmentation, preprocessing, image sharpening, adaptive binarization, character segmentation, and post-processing. Each stage was designed to progressively improve image quality and enhance structural features, ultimately enabling accurate extraction of individual characters.

The system was evaluated using a combination of augmented and real-world inscription images, and the results demonstrated the effectiveness of the proposed approach in handling noise, low contrast, and complex background textures.

4.2. Summary of Key Contributions

This study makes several important contributions to the field of inscription image processing and digital image analysis.

Firstly, the research demonstrates the effectiveness of a progressive enhancement strategy in improving segmentation performance. Instead of relying on a single processing step, the system integrates multiple stages that collectively transform degraded images into structured representations. This approach significantly improves the clarity of character boundaries and enhances segmentation accuracy.

Secondly, the study highlights the importance of image sharpening as a critical intermediate stage. The results show that sharpening plays a vital role in restoring weak and degraded edges, making it easier for segmentation algorithms to detect character boundaries. This finding emphasizes the need to include edge enhancement techniques in inscription processing pipelines.

Thirdly, the use of adaptive binarization is shown to be highly effective in handling real-world variability. By applying local thresholding, the system successfully separates foreground characters from complex and uneven backgrounds, overcoming limitations associated with global thresholding methods.

Another key contribution is the identification of strong interdependencies between processing stages. The research confirms that the performance of segmentation is directly influenced by the quality of preprocessing and enhancement. This highlights the importance of designing integrated systems where each stage supports and enhances the next.

Finally, the study provides a practical and modular framework that can be extended for applications such as optical character recognition (OCR), historical document analysis, and cultural heritage preservation.

4.3. Key Findings

The experimental results and analysis led to several important findings.

One of the most significant findings is that segmentation accuracy improves when applied after progressive enhancement. The combination of preprocessing, sharpening, and binarization creates optimal conditions for extracting character structures.

Another important finding is the critical role of image quality in determining system performance. While the proposed pipeline effectively enhances degraded images, its performance is ultimately limited by the quality of the original input. In cases where images are severely degraded or lack sufficient clarity, the system struggles to recover meaningful structural information.

The study also highlights the impact of stone surface texture on segmentation. Natural patterns such as cracks, grains, and irregularities often resemble character strokes, leading to false detections. This presents a significant challenge in inscription image processing and requires further research to address effectively.

Additionally, the results confirm that adaptive binarization is more suitable for real-world inscription images compared to traditional global thresholding methods, as it handles uneven illumination more effectively.

4.4. Limitations of the Study

Despite the promising results, several limitations of the study must be acknowledged.

One limitation is the system's reduced performance when processing extremely degraded inscriptions. In such cases, where characters are heavily eroded or partially missing, the system is unable to fully reconstruct the original structure.

Another limitation is the issue of character fragmentation, where broken strokes result in multiple segments for a single character. This affects segmentation accuracy and may impact downstream tasks such as recognition.

The system also faces challenges in handling overlapping or closely spaced characters, which may be incorrectly grouped into a single segment. This is particularly problematic in inscriptions with irregular spacing or stylized writing.

A critical limitation is the dependency on input image quality. If the captured image is not clear or contains excessive noise and texture interference, the effectiveness of the processing pipeline is significantly reduced. This emphasizes the importance of proper image acquisition techniques.

Finally, the current system relies on traditional image processing methods, which may not fully capture complex patterns and variations present in highly degraded images.

4.5. Practical Implications

The findings of this research have important implications for real-world applications.

The proposed system can be used for digital preservation of historical inscriptions, enabling the conversion of degraded images into structured and analyzable formats. This is particularly valuable for preserving cultural heritage and historical records.

The system also has potential applications in automated text extraction and recognition, where segmented character outputs can be used as input for machine learning models. This can facilitate the development of OCR systems for ancient and historical texts.

In addition, the research highlights the importance of high-quality image acquisition in practical applications. Proper lighting, camera positioning, and resolution are essential for achieving optimal results, and should be considered during data collection.

The modular design of the system also allows it to be adapted for other image processing tasks, making it a flexible solution for various domains.

4.6. Future Work

Several directions for future research can be identified based on the findings and limitations of this study.

One potential improvement is the integration of deep learning-based models for image enhancement and segmentation. These models have the ability to learn complex patterns and may provide better performance in handling highly degraded images.

Another area for future work is stroke reconstruction, where fragmented character components are merged to form complete characters. This would improve segmentation accuracy and enhance the usability of the output.

Improving the handling of overlapping characters is also an important direction. Advanced segmentation techniques, such as instance segmentation or contour-based methods, could be explored to address this issue.

Additionally, incorporating texture-aware processing techniques could help differentiate between actual characters and background patterns, reducing false detections caused by stone surfaces.

Finally, extending the system to include end-to-end recognition capabilities, such as integrating OCR models, would enable complete automation from image input to text output, significantly increasing the practical value of the system.

4.7. Final Remarks

In conclusion, this study successfully demonstrates that a carefully designed multi-stage image processing pipeline can significantly improve the quality and interpretability of degraded inscription images. By addressing key challenges such as noise, low contrast, uneven illumination, and structural degradation, the proposed system provides an effective solution for character segmentation.

While certain limitations remain, particularly in handling extremely degraded images and complex textures, the research establishes a strong foundation for further development in this field. With the integration of advanced techniques and improved data acquisition practices, the proposed approach has the potential to contribute significantly to the advancement of digital inscription analysis and cultural heritage preservation.

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