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Comparative Analysis of Canny Edge Detection Involving Hough Transform and Chuan Method in Forensic Segmentation of Firing Pin Impressions: Implications for Criminal Justice Studies

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Abstract
This paper provides a comprehensive comparison of two widely used automatic image segmentation techniques—Canny edge detection combined with the Hough transform, and the Chuan method. Both techniques are applied to forensic image segmentation, specifically firing pin impressions. The results indicate that the Canny edge detection and Hough transform method achieves superior segmentation accuracy, with an average Jacard similarity measure(JSM) of 94.1%. In contrast, the Chuan method, although computationally more efficient, achieves a lower average JSM of 90.5%. The study concludes that for high-stakes applications such as forensic analysis, the Canny method is more suitable, while the Chuan method is better suited for large-scale applications where high precision is less critical.
Keywords: Automatic Image Segmentation, Canny Edge Detection, Hough Transform, Forensic Image Analysis, Firing Pin Impressions.

Introduction

In recent years, image segmentation techniques have become increasingly vital across a wide range of fields, including medical imaging, autonomous systems, and forensic analysis. The fundamental goal of image segmentation is to partition an image into meaningful regions, typically by identifying object boundaries or differentiating between various regions of interest. Accurate segmentation is particularly crucial in high-stakes applications like forensic image analysis, where errors can compromise investigations and judicial outcomes. Among the most prominent techniques in this domain are edge detection methods, which facilitate the identification of object boundaries by detecting sharp discontinuities in image intensity values.

Edge detection methods, such as the Canny edge detector, have long been considered one of the most effective tools for image segmentation. The Canny method provides an optimal balance between detection accuracy, edge localization, and noise resistance, making it a preferred choice in numerous fields. It has been applied in various image analysis tasks, ranging from medical imaging to automated driving systems. For example, Shi et al. (2020) employed the Canny edge detection algorithm to improve precision in target detection within autonomous driving environments, where object identification is essential for safety and navigation (Shi et al., 2020). In another study, Memiş et al. (2019) applied the Canny operator in orthopedic image segmentation, demonstrating its ability to accurately detect and segment the femoral head in hip joint MR images (Memiş et al., 2019). These studies highlight the versatility and effectiveness of Canny edge detection in a variety of settings.

In forensic analysis, the segmentation of firing pin impressions in ballistic images is a critical task, as these impressions can serve as key evidence in identifying firearms used in criminal activities. The accuracy of segmentation directly impacts the ability to match ballistic evidence to specific firearms, which underscores the importance of using reliable segmentation techniques. Hough transform, another widely adopted technique, is often combined with edge detection methods like Canny to enhance segmentation performance. Hough transform is especially effective in detecting geometric shapes, such as lines and circles, within images, which can be useful in forensic applications for identifying distinct patterns in firing pin impressions. Liang and Liang (2020) demonstrated the effectiveness of the Hough transform in maritime surveillance systems, where the algorithm was used to detect the horizon line in sea and sky images under challenging conditions, thereby improving segmentation accuracy in the presence of occlusions and low visibility (Liang & Liang, 2020). This study illustrates the robustness of the Hough transform when applied to real-world scenarios with complex visual inputs.

While both the Canny edge detection and Hough transform techniques have proven their efficacy in a variety of domains, their specific applications to forensic image segmentation, particularly in the context of firing pin impressions, are less explored. This paper aims to address this gap by providing a comparative analysis of these two methods, Canny edge detection combined with the Hough transform and the Chuan method in forensic image segmentation tasks. The Chuan method, although computationally more efficient, has been reported to achieve slightly lower accuracy than the Canny-Hough combination. In their research on medical image segmentation, Xu et al. (2021) compared several edge detection techniques, including Canny, Sobel, Prewitt, and Roberts methods, concluding that the Canny method provided superior edge detection accuracy in images with complex structures (Xu et al., 2021). This supports the notion that Canny, when combined with Hough, offers robust results in scenarios requiring precision, such as forensic investigations.

Several recent studies have emphasized the significance of edge detection techniques in improving segmentation accuracy. Abidin et al. (2020) conducted a comprehensive study on various edge detection algorithms for image segmentation, focusing on the effects of noise suppression and false edge detection. Their findings indicated that the Canny method outperformed other algorithms, such as Sobel and Log, in terms of noise resistance and edge localization (Abidin et al., 2020). Similarly, Zhou et al. (2021) applied edge detection techniques to agricultural image segmentation, where they found that the Canny method provided the most accurate edge detection results, especially in images with varying contrast levels (Zhou et al., 2021). In forensic image segmentation, where precision is paramount, these studies suggest that the Canny-Hough combination offers substantial benefits over more computationally efficient methods like the Chuan technique.

Moreover, image segmentation techniques based on edge detection are continuously evolving, with new approaches being developed to further enhance accuracy and computational efficiency. For instance, Widiyanto et al. (2019) introduced a quantum-enhanced version of the Canny edge detection method, which showed improved performance in medical imaging by providing more precise edge detection while maintaining computational efficiency (Widiyanto et al., 2019). This demonstrates that advancements in edge detection technologies can have a direct impact on fields requiring precise image analysis, including forensic science. Similarly, Peng and Zhao (2019) developed a modified Canny algorithm for liver CT image segmentation, achieving higher adaptability and precision in handling uneven image quality, further underscoring the potential of edge detection in improving segmentation outcomes (Peng & Zhao, 2019).

Given the increasing demand for accurate and efficient image segmentation techniques in forensic science, this paper provides a comparative analysis of Canny edge detection combined with the Hough transform and the Chuan method. The study aims to evaluate the strengths and weaknesses of each method in the context of forensic image segmentation, particularly in the analysis of firing pin impressions. By drawing on recent advancements in edge detection and segmentation technologies, this research seeks to offer valuable insights into the most suitable techniques for high-stakes forensic applications, where segmentation accuracy is crucial for ensuring reliable evidence analysis.

Research Background and Motivation

The field of image segmentation has seen significant advancements over the past few decades, driven by the increasing need for precise and efficient methods in various high-stakes applications. Image segmentation, a critical component in image processing, aims to divide an image into meaningful regions or objects to facilitate further analysis. In forensic science, segmentation is used to isolate and analyze key features in images that serve as critical evidence. One such application is the segmentation of ballistic images, particularly firing pin impressions, which play an essential role in firearm identification during forensic investigations. Accurate segmentation of these impressions can link evidence to a specific firearm, making precision paramount in forensic settings.

Several techniques have emerged to address the challenges of image segmentation, with edge detection methods standing out as fundamental tools for identifying object boundaries in images. Among these methods, the Canny edge detection algorithm has garnered widespread attention for its balance between accuracy, edge localization, and noise reduction. In forensic science, the need for precise boundary detection has driven researchers to explore the potential of combining Canny edge detection with other segmentation techniques, such as the Hough transform. The Hough transform, which detects geometric shapes like lines and circles, complements edge detection methods by enhancing segmentation outcomes in images with distinct patterns, such as ballistic firing pin impressions (Abd Razak et al., 2017), (Abd Razak et al., 2020). Studies have shown the effectiveness of the Canny-Hough combination in various fields, including autonomous driving, medical imaging, forensic, and industrial applications (Abd Razak et al., 2020), (Shi et al., 2020), (Zhou et al., 2021).

The forensic field, with its unique requirements for accuracy and reliability, benefits greatly from advances in edge detection and segmentation methods. A high degree of precision is required when dealing with ballistic evidence, as even small inaccuracies can lead to false matches or misidentifications. The Canny edge detection method has proven to be highly adaptable to forensic applications, providing accurate segmentation in challenging conditions such as noisy images or images with low contrast. In a study by Abidin et al. (2020), the Canny method outperformed other edge detection algorithms in terms of noise resistance and edge detection accuracy, making it ideal for use in forensic applications where precision is paramount (Abidin et al., 2020).

Moreover, the Hough transform adds another layer of precision, particularly when detecting shapes like circles and lines, which are common in ballistic images. Recent research has demonstrated the robustness of the Hough transform in detecting such patterns in complex environments, further supporting its use in forensic analysis (Cheng et al., 2021). For example, Liang and Liang (2020) applied the Hough transform to maritime surveillance, successfully detecting horizons in sea-sky images despite challenging conditions such as occlusion and low visibility. This illustrates the transform's ability to maintain high detection accuracy even in noisy or complex images (Liang & Liang, 2020).

The combination of Canny edge detection and Hough transform has also been explored in other fields, demonstrating its versatility and potential in forensic image analysis. For instance, Iqbal et al. (2019) implemented both algorithms in the processing of high-resolution video streams, showing that these methods can efficiently handle large-scale data while maintaining high accuracy and computational efficiency. Their research highlighted the scalability of these algorithms, further supporting their applicability in forensic settings where large volumes of image data may need to be processed (Iqbal et al., 2019).

Despite the success of these methods in various domains, the forensic application of edge detection and shape detection techniques, particularly in ballistic image segmentation, remains underexplored. The challenge lies in achieving a balance between computational efficiency and segmentation accuracy, especially in high-stakes environments where small errors can lead to significant consequences. In this context, the Chuan method offers a computationally efficient alternative, though it sacrifices some degree of precision compared to the Canny-Hough combination. Research in medical imaging has shown that while the Chuan method is faster, it may not perform as well as more complex algorithms in tasks requiring high precision (Xu et al., 2021).

In light of these advancements, this research aims to compare the Canny-Hough method and the Chuan method in the specific context of forensic image segmentation, focusing on the analysis of firing pin impressions. By evaluating the performance of these techniques in terms of segmentation accuracy, computational efficiency, and adaptability to various image conditions, this study seeks to provide valuable insights into the most suitable methods for forensic applications. As forensic science continues to evolve, the need for reliable and efficient image segmentation techniques will only grow, making this research timely and relevant.

In summary, the combination of Canny edge detection and Hough transform has proven its value in multiple fields requiring precision and accuracy. However, the forensic application of these techniques, particularly in ballistic image segmentation, requires further exploration. By comparing the Canny-Hough combination with the Chuan method, this research seeks to contribute to the development of more reliable and efficient segmentation techniques in forensic science, where accuracy is critical.

Methodology

In this study, image segmentation, which is a critical initial step in image processing for various applications involving video images and computer vision, is explored. Image segmentation is widely employed in applications for image identification and classification across diverse fields such as forensic, medicine and agriculture.

Segmentation testing of the full image of firing pin impression was conducted on 250 images, with 50 images from each of Pistols A, B, C, D, and E. This research presents a comparison of firing pin impression segmentation between the Chuan technique and Canny Edge Detection and Hough Transform technique.

The segmentation method for the region of interest in firing pin impression, as proposed by Chuan et al. (2017), consists of the following stages:

Stage 1: Laplace Sharpening Filter Application

The Laplace Sharpening Filter (LF) is applied to the image. This filter enhances the edge intensity of the explosive pin impact in image P, significantly improving the visibility of boundary details. By emphasizing edge contrasts, the LF ensures that key features of the image are more distinguishable. The resultant image after this step is referred to as PLF, representing the sharpened version of the original image.

Stage 2: Histogram Normalization

In this stage, histogram normalization (HN) is applied to the PLF image. The purpose of this step is to compress the dynamic range of intensity values within the image, effectively normalizing the intensity distribution. This normalization facilitates improved contrast adjustment, ensuring that the full range of pixel intensity levels is utilized for optimal segmentation. The output from this stage is labeled as the PHN image.

Stage 3: Shannon Entropy-Based Thresholding

Following histogram normalization, the Shannon Entropy-based thresholding method (SE) is implemented. This step transforms the previously normalized PHN image into a binary format, creating a clearer distinction between the foreground (region of interest) and background. This process leverages Shannon entropy to select the optimal threshold value, maximizing information content in the resultant binary image, denoted as PB. The binarization at this stage is crucial for subsequent shape fitting.

Stage 4: Circle Fitting Using the Least Squares Estimator

The final stage involves the application of the least squares estimator to fit an unweighted circle to the binary image PB. This estimator calculates the center coordinates (x, y) and the radius (r) of the circular region that best approximates the boundary of the explosive pin impact area. The result is a highly precise estimation of the region of interest (ROI) within the image, representing the full extent of the explosive pin impact. This estimation is essential for detailed analysis and further processing tasks, ensuring accurate segmentation.

This four-stage methodology of Chuan method offers a robust and efficient approach to segmenting firing pin impression images, combining computational efficiency with accuracy. The use of Laplace sharpening, histogram normalization, entropy-based thresholding, and least squares estimation ensures that the method is capable of handling both high-noise environments and complex image structures. The versatility and precision of this approach make it particularly suited for applications in fields where the segmentation of complex patterns is critical.

Next, the steps for segmentation method using the Canny edge detection algorithm and Hough transform are as follows (Gonzales, 2018):

1. **Gaussian Filter Application**: The algorithm starts by applying a Gaussian filter to the image in order to reduce noise, which is crucial for enhancing the accuracy of edge detection.
2. **Gradient Computation**: The local gradient, denoted as $G(x, y)$ and the gradient orientation angle θ, are calculated using the following formulas:
$$G(x,y) = \sqrt{G_x^2 + G_y^2} \quad \text{and} \quad \theta = arctan\left(\frac{G_y}{G_x}\right)$$
These equations help in determining the intensity and direction of edges in the image.
3. **Non-Maximum Suppression**: After computing the gradients, non-maximum suppression is applied. This step involves thinning out the edges to ensure that only the most prominent edges are preserved, while weaker edges are suppressed.
4. **Hysteresis Thresholding**: Finally, hysteresis thresholding is performed. This process involves applying two thresholds—upper and lower limits—to detect strong edges and suppress weaker ones. This ensures that the edges detected are continuous and robust.
5. **Set Circle Center (x, y) to Edge Pixel**: Initialize the center of the circle at the location of an edge pixel identified in the image.
6. **Define Radius (r)**: Iterate the radius value from 0 to 200, representing potential circle sizes.
7. **Draw Circle**: For each radius value, draw a circle centered at the defined coordinates (x, y) using the current radius.
8. **Voting Process in the Accumulator**: Conduct a voting process where the points of intersection from the drawn circles are collected in an accumulator. The formula for the accumulator is:
$$H(x,y,r) = \sum_{i=1}^{n} h(x_i, y_i, x, y, r).$$
This helps identify the best fitting circles in the image.
9. **Determine Circle Center**: The location where the most intersections occur within the accumulator defines the center of the circle.
where (x_i, y_i) is the edge pixel point and:

$$h(x_i, y_i, x, y, r) = (x_i - x)^2 + (y_i - y)^2 - r^2.$$

The center of the circle, (x, y) = the point with the most intersections.

10. **Calculate Radius**: Finally, the radius is calculated as:

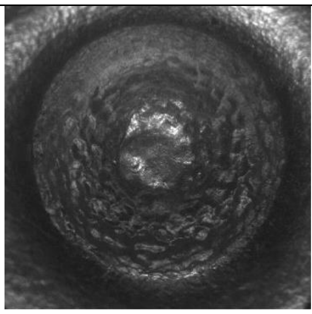
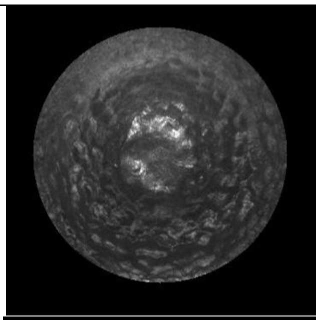
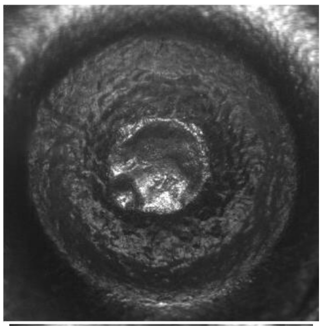
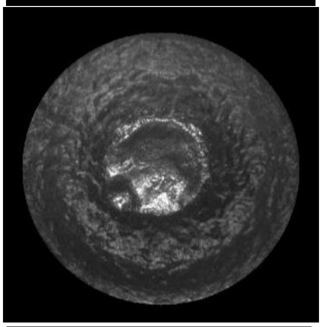
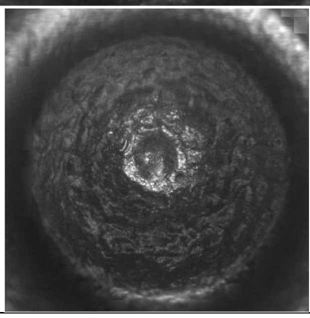
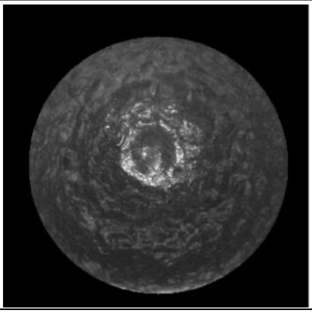
$$r = \sqrt{x^2 + y^2}$$

which gives the radius of the detected circle.

This method is widely used for detecting circular shapes in an image, providing a robust way to identify circular edges even under noisy conditions.

Results and Discussion

Figure 1 illustrates the results of image segmentation on the firing pin impression for the first image from each of Pistols A, B, C, D, and E. A visual inspection reveals that images A001FP3, B001FP3, and D001FP3 have been segmented almost perfectly. However, the segmentation results for images C001FP3 and E001FP3 appear to be less accurate (Abd Razak et al., 2017)

Image	Original Image	Segmented image
A001FP3		
B001FP3		
C001FP3		

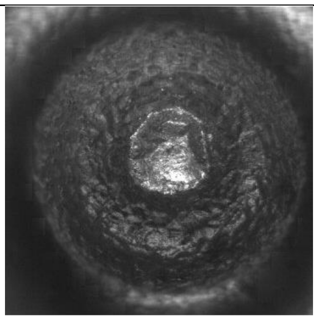
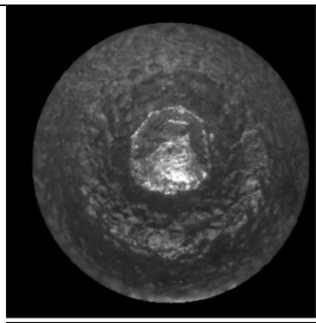
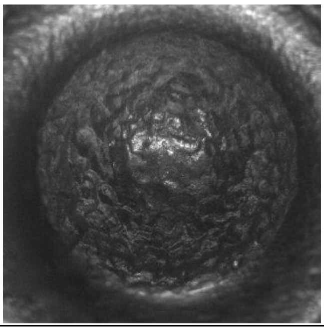
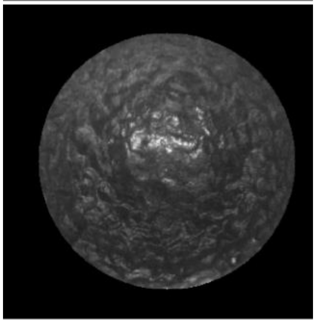
D001FP3		
E001FP3		

Figure 1: Segmentation results of the full image of firing pin impression for the first image of each Pistol A, B, C, D, and E.

Table 1 below shows that each pistol was almost successfully segmented, as all the average segmentation accuracy percentages based on JSM exceeded 90%. The segmentation performance of the firing pin impression for pistol B was the highest, at 95.6%. Meanwhile, the segmentation performance for pistol C was the lowest, at 91.6%.

Table 1
Segmentation performance based on the average JSM percentage using the Canny edge detection technique and Hough transform

Pistol	**Purata peratus ketepatan segmentasi berdasarkan JSM**
A	94.3 %
B	95.6 %
C	91.6 %
D	94.9 %
E	94.0 %

For comparison, the JSM metric was also used to evaluate the segmentation performance of the full image of firing pin impression based on Chuan's recommended technique. Table 2 presents the average JSM percentage based on different pistols from the same model. It was found that images from pistols A, C, and E were successfully segmented with performance exceeding 90%, but not for B and D.

Table 2
Segmentation performance based on the average JSM percentage using Chuan's recommended technique.

Pistol	Purata peratus ketepatan segmentasi berdasarkan JSM
A	91.7 %
B	89.1 %
C	90.5 %
D	88.6 %
E	92.6 %

Table 3 below shows a comparison of segmentation performance using the Canny edge detection technique and Hough transform with Chuan recommended technique. The segmentation performance of firing pin impression from all five pistols using the Canny technique and Hough transform exceeded 90%. Meanwhile, the segmentation performance using Chuan recommended technique that exceeded 90% was achieved for the firing pin impression from pistols A, C, and E. Overall, the segmentation performance for the full image of firing pin impression from all pistols was 94.1% using the Canny edge detection technique and Hough transform, while the segmentation performance using Chuan recommended technique was 90.5%. This indicates that the Canny edge detection technique and Hough transform are superior to Chuan recommended technique for the segmentation of firing pin impression.

Table 3
Comparison of segmentation performance using the technique of Canny edge detection and Hough transform with Chuan's recommended technique."

Pistol	JSM Metric(%)	
	Technique of Canny and Hough transform	Chuan technique
A	94.3	91.7
B	95.6	89.1
C	91.6	90.5
D	94.9	88.6
E	94.0	92.6
Overall	94.1	90.5

Conclusion and Future Work

This study conducted a comparative analysis of two image segmentation techniques—Canny edge detection combined with the Hough transform, and Chuan's method—in the forensic examination of firing pin impressions, a critical task in criminal justice investigations. The results show that the Canny edge detection and Hough transform technique outperformed Chuan's method in terms of segmentation accuracy, achieving an average JSM of 94.1%, compared to 90.5% for Chuan's method. Despite its lower precision, Chuan's method offers computational efficiency, making it more suitable for large-scale forensic applications. As highlighted by Xu et al. (2021) and Abidin et al. (2020), reliable image segmentation is essential for ensuring the accuracy of forensic evidence, which directly impacts judicial outcomes. Thus, these findings contribute to enhancing the quality and reliability of forensic evidence, playing a significant role in improving criminal investigations and judicial processes, ultimately benefiting society.

Future efforts should focus on developing hybrid approaches that combine the computational efficiency of Chuan's method with the accuracy of the Canny-Hough technique. With advancements in machine learning and AI-driven edge detection algorithms, as suggested by Shi et al. (2020) and Widiyanto et al. (2019), segmentation accuracy can be further enhanced while optimizing processing times. Expanding these methods to other types of ballistic and forensic evidence, such as toolmarks and bullet striations (Zhou et al., 2021), can strengthen their applicability across various criminal justice cases. Additionally, the development of real-time, automated forensic image segmentation systems would not only improve accuracy but also expedite the resolution of cases, significantly benefiting law enforcement and the broader society by ensuring timely justice.

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