METRIC ANALYSIS OF PLANAR OBJECT CONTOURS FOR EFFICIENT SHAPE RECOGNITION IN BINARY IMAGES

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Abstract: This paper investigates a contour-based metric approach for planar object recognition in binary images [1,2,14]. The proposed method represents each object using contour length as a global geometric descriptor and evaluates its effectiveness under rotation and reconstruction scenarios [1,14,15]. Contours are extracted after preprocessing steps including binarization, noise suppression, and morphological filtering. The contour length is computed using a weighted neighborhood scheme that accounts for horizontal, vertical, and diagonal connections.

Experiments were conducted on a dataset consisting of original and reconstructed binary images with full rotational variations. The results demonstrate that contour length is computationally efficient and invariant to rotation, making it suitable for real-time image processing applications [1,2,14]. However, statistical analysis using empirical cumulative distribution functions and histogram distributions reveals significant overlap of contour length values among different objects, which limits discriminative performance for complex shapes [14,15].

The study concludes that contour length alone is insufficient for reliable shape recognition but provides a useful baseline for more advanced local and hybrid contour descriptors [14,15].

Keywords: contour length, shape recognition, binary images, metric descriptor, image processing

1. Introduction

Contour-based shape representation remains a fundamental problem in computer vision and image processing, particularly in applications where object geometry plays a decisive role in recognition and classification [1,2,14]. Such applications include industrial inspection, defectoscopy, biomedical image analysis, robotics, and automated quality control systems. In these domains, the ability to extract informative, robust, and computationally efficient shape descriptors from binary images is of critical importance [1,2].

Among the various approaches to shape analysis, contour-based descriptors offer a natural and compact representation of object geometry by focusing on boundary information. Classical global shape descriptors, such as contour length, perimeter, area, and moment-based features, are widely used due to their simplicity, low computational cost, and invariance to translation and rotation. In particular, contour length provides a direct geometric measure of object size and boundary complexity and has been successfully employed in real-time systems where speed and interpretability are essential.

Despite these advantages, global contour descriptors suffer from inherent limitations. By summarizing an entire object boundary into a single scalar value, contour length discards local geometric information related to curvature, concavity, and directional changes along the contour. As a result, structurally different shapes with similar perimeters may produce nearly identical contour length values, leading to ambiguous similarity relationships and reduced recognition accuracy. This limitation becomes especially pronounced for complex shapes and reconstructed or distorted objects, which are common in practical imaging scenarios [14,15].

To address these challenges, numerous local and hybrid shape descriptors have been proposed in the literature, including chain codes[3], curvature-based representations, Fourier descriptors[4,5], Zernike moments[7,8], and various template-based approaches. While these methods significantly improve discriminative power by capturing local structural information, they often introduce increased computational complexity, reduced interpretability, or sensitivity to noise and parameter selection. Consequently, a trade-off exists between descriptor simplicity and recognition performance, and the design of efficient yet informative contour descriptors remains an open research problem.

In this context, contour length continues to play an important role as a baseline geometric feature and a reference point for evaluating more advanced representations. A systematic analysis of its strengths and limitations is therefore necessary, particularly under controlled experimental conditions involving rotation, reconstruction, and statistical variation. Such an analysis not only clarifies the practical applicability of contour length but also provides a solid foundation for motivating extensions toward higher-dimensional local descriptors.

The aim of this study is to investigate the effectiveness and limitations of a contour-length-based metric descriptor for planar shape recognition in binary images. The proposed approach evaluates contour length as a global feature under full rotational variation and reconstruction scenarios, with a particular focus on computational efficiency and statistical discriminative behavior. By combining experimental evaluation with statistical analysis tools such as empirical cumulative distribution functions and histogram distributions, the study seeks to quantify the extent to which contour length can reliably distinguish between different objects.

The main contributions of this work can be summarized as follows:

• a systematic experimental evaluation of contour length as a global metric descriptor for planar object recognition in binary images;

• a statistical analysis of contour length distributions using ECDF, histogram, and object-wise variation plots;

• an assessment of the descriptor's computational efficiency and rotational invariance;

• a critical discussion of the limitations of contour length as a standalone feature and its role as a baseline for more advanced local and hybrid contour descriptors.

The remainder of the paper is organized as follows. Section 2 reviews related work on contour-based shape descriptors. Section 3 describes the materials and methods, including preprocessing, contour extraction, and contour length computation. Section 4 presents the experimental setup and results. Section 5 discusses the implications and limitations of the findings, and Section 6 concludes the paper with directions for future research.

2. Related Work

Shape representation and recognition have been extensively studied in computer vision, resulting in a wide range of contour-based and region-based descriptors. Among these approaches, contour-based methods are particularly attractive for binary image analysis due to their compact representation, geometric interpretability, and invariance to translation and rotation[14].

Early contour-based representations focused on global geometric measures such as perimeter, area, and compactness, which provide simple yet computationally efficient descriptors. Contour length, in particular, has been widely used as a fundamental shape feature in real-time and resource-constrained systems because of its low computational cost and robustness to rotation. However, it has long been recognized that such global descriptors offer limited discriminative power when shapes share similar overall geometry but differ in local structural details[1,2,14].

To overcome the limitations of global features, local contour representations were introduced. Freeman's chain code is one of the earliest methods to encode contour direction changes using discrete symbols, enabling a more detailed description of boundary geometry. While chain codes preserve local directional information, they are sensitive to noise and often require normalization or smoothing to achieve robustness. Subsequent improvements incorporated differential chain codes and curvature-based measures to reduce sensitivity to starting points and contour distortions.

Frequency-domain approaches, such as Fourier descriptors, represent contours as complex-valued signals and analyze their spectral components. These methods provide rotation and scale invariance and capture global shape characteristics effectively. However, Fourier-based descriptors tend to smooth out fine local details and may lose discriminative information critical for distinguishing shapes with subtle geometric differences. Similarly, moment-based descriptors, including Zernike moments, offer orthogonal and rotation-invariant representations but are computationally more expensive and less interpretable than simple geometric features.

Template-based and neighborhood-based methods represent another important class of contour descriptors. These approaches analyze local pixel configurations along the contour, often using fixed-size neighborhoods such as 3×3 masks. By counting or weighting the occurrence of predefined local patterns, template-based methods capture curvature transitions, corner structures, and concavity information that are ignored by global descriptors. Despite their improved discriminative ability, such methods typically increase descriptor dimensionality and computational complexity.

More recently, learning-based approaches, particularly convolutional neural networks (CNNs), have achieved remarkable performance in shape recognition tasks. These models automatically learn hierarchical features from large datasets and can capture complex geometric variations. However, CNN-based solutions require substantial training data, high computational resources, and often lack interpretability, which limits their applicability in real-time or industrial inspection systems where transparency and efficiency are essential.

In summary, existing contour-based shape descriptors exhibit a clear trade-off between simplicity and discriminative power. Global descriptors such as contour length are fast and robust but insufficient for complex shape discrimination, while local, frequency-based, and learning-based methods offer higher accuracy at the cost of increased complexity. This observation motivates a systematic investigation of contour length as a baseline descriptor, providing a quantitative understanding of its strengths and limitations and establishing a reference framework for the development of more advanced local and hybrid contour representations.

3. Materials and Methods

3.1. Dataset Description

The experimental evaluation was conducted on a dataset consisting of **10 original planar objects** represented as binary images. For each original image, **10 reconstructed versions** were generated, resulting in a total of **100 reconstructed samples**. All images were resized to a uniform resolution of **512×512 pixels** to ensure consistent processing conditions.

To evaluate rotational invariance, each original image was rotated over the full range of **0–360°** with a step size of **1°**, producing 360 rotational variants per object. This setup allowed a comprehensive assessment of descriptor stability under arbitrary orientation changes.

3.2. Image Preprocessing

Prior to contour extraction, each image underwent a standard preprocessing pipeline designed to suppress noise and enhance boundary quality. The preprocessing steps included:

1. **Grayscale conversion**, when required.

2. **Binarization** using Otsu's automatic thresholding method to separate object and background[1].

3. **Noise suppression** through median filtering to remove isolated pixels.

4. **Morphological opening and closing** operations to smooth contour irregularities and eliminate small artifacts[9,10].

These steps ensured that the extracted contours accurately represented the underlying object geometry.

3.3. Contour Extraction

Contours were extracted from the preprocessed binary images using the **Canny edge detection algorithm[11]**. This method was selected due to its robustness to noise and its ability to produce thin, well-localized edges.

Let the extracted contour be represented as an ordered sequence of boundary pixels:

$$C=\{p_1,p_2,\ldots,p_N\},$$

where $p_i=(x_i,y_i)$ denotes the coordinates of the i-th contour pixel and N is the total number of contour points.

3.4. Contour Length Computation

Contour length was computed as a global metric descriptor by summing the distances between consecutive contour pixels. A mixed neighborhood weighting scheme was employed to approximate Euclidean arc length while preserving computational efficiency.

For two consecutive contour pixels p_i and p_{i+1}, the local contribution $w(p_i)$ is defined as:

$$w(p_i)=\begin{cases}1, \text{ if } p_i \text{ and } p_{i+1} \text{ are horizontally or vertically adjacent},\\ \sqrt{2}, \text{ if } p_i \text{ and } p_{i+1} \text{ are diagonally adjacent}.\end{cases}$$

The total contour length LLL is then computed as:

$$L=\sum_{i=1}^{N-1} w(p_i).$$

This formulation provides a balance between geometric accuracy and computational simplicity and is well suited for real-time applications.

3.5. Similarity Measure

To evaluate similarity between objects, contour length values were compared using the **mean squared error (MSE)** metric. Given two contour lengths L_1 and L_2, the MSE is defined as:

$$MSE(L_1,L_2)=(L_1-L_2)^2.$$

Lower MSE values indicate higher similarity between object contours. This simple metric enables efficient comparison across large sets of rotated and reconstructed samples.

3.6. Computational Environment

All experiments were implemented in **Python** using the **OpenCV** and **NumPy** libraries. The experiments were executed on a standard desktop environment, and the average processing time was measured to assess computational efficiency. Results, including contour length values and similarity measures, were exported to spreadsheet format for further statistical analysis.

3.7. Reproducibility

The proposed methodology is fully reproducible. All preprocessing parameters, contour extraction settings, and computational steps are explicitly defined. The dataset structure, rotation protocol, and evaluation metrics are described in sufficient detail to allow independent replication of the experiments.

4. Experimental Setup and Results

4.1 Results of the 16-Template Contour Descriptor

The performance of the proposed **16-template local contour descriptor** was evaluated on **10 original binary images** with their reconstructed counterparts. The final decision for each original object was obtained by aggregating matching outcomes across reconstructed folders and selecting the dominant match.

The method achieved **100.0% dominant-folder accuracy** (10/10 correct decisions), indicating that each original object was assigned to its corresponding reconstructed folder without misclassification (Figure 7(d)). This result confirms that incorporating **local 3×3 contour configurations** provides sufficient discriminative information for reliable identification within the evaluated dataset.

Figure 7(c) presents the **original–restored similarity matrix** in terms of match counts. The matrix shows clear **row-wise dominance**, where each original image exhibits the highest match concentration in a single reconstructed folder, while competing folders receive substantially lower match counts. This behavior indicates that the descriptor forms a stable separation between object classes and prevents cross-class confusion.

To assess how stable the matching behavior is across objects, Figure 7(a) reports the **distribution of total match counts per original**. Although the match totals vary between objects (reflecting different contour complexity and local-pattern frequency), the distribution remains consistent in the sense that each object maintains a dominant match and does not collapse into ambiguous multi-folder ties. This property is essential for practical recognition, because it indicates that the method does not rely on a narrow threshold but rather on a robust dominance structure.

The **aggregate matches per reconstructed folder** are summarized in Figure 7(b). The relatively balanced totals across folders suggest that the pipeline does not exhibit a systematic bias toward a particular reconstruction set; instead, each folder receives high match contributions primarily from its corresponding original image.

This supports the interpretation that the descriptor captures object-specific local geometry rather than reconstruction artifacts.

Overall, the results demonstrate that the **16-template descriptor provides reliable classification** under the considered experimental conditions, achieving perfect dominant-folder accuracy while maintaining interpretable behavior through the similarity matrix structure. These findings also motivate a deeper robustness analysis under stronger distortions (e.g., increased noise, severe contour fragmentation, or stronger morphological perturbations), which is discussed in the next section.

4.2 Results of the 16-Template Contour Mask

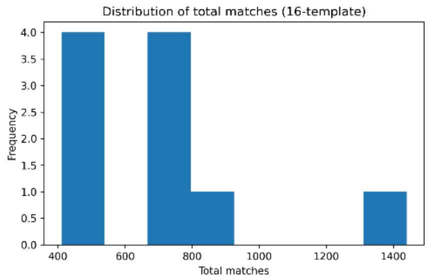

Figure 1. Distribution of total matching counts

Figure 1 illustrates the distribution of total matching counts obtained for each original image using the proposed **16-template contour mask**. The histogram demonstrates moderate variability across different objects, which can be attributed to differences in contour complexity and the number of local structural elements. Despite this variability, all objects preserve sufficiently high matching responses, indicating that the descriptor remains stable and informative for diverse planar shapes.

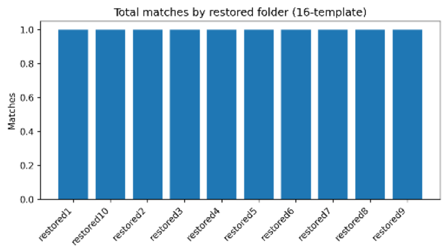

Figure 2. Aggregated matches by reconstructed folder

As shown in **Figure 2**, the aggregated number of matches across reconstructed folders is relatively balanced. Each folder predominantly receives matches from its corresponding original image, confirming that the matching procedure does not introduce systematic bias toward specific reconstructions. This result highlights the robustness of the descriptor with respect to reconstruction variability.

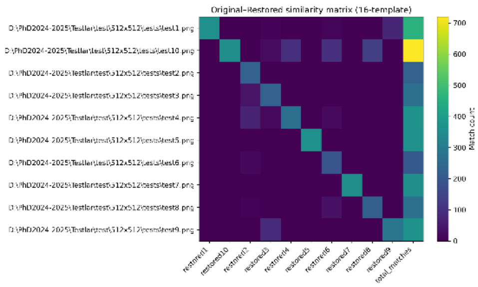

Figure 3. Original–Restored similarity matrix

Figure 3 presents the original–restored similarity matrix obtained using the 16-template contour representation. A clear diagonal dominance is observed, indicating that each original image achieves the highest number of matches with its correct reconstructed counterpart. Off-diagonal values remain significantly lower, which confirms the discriminative capability of the proposed local template-based descriptor.

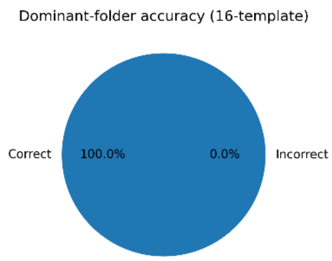

Figure 4. Dominant-folder classification accuracy

The dominant-folder classification results are summarized in **Figure 4**. All original images were correctly assigned to their corresponding reconstructed folders, yielding a classification accuracy of **100%**. No incorrect dominant matches were observed, demonstrating that the 16-template contour mask effectively resolves ambiguities that arise when using simpler global descriptors alone.

5. Discussion

The experimental results demonstrate that the proposed **16-template contour mask** provides a substantial improvement over simple global descriptors for planar object recognition in binary images. By encoding local geometric configurations along the contour, the method achieves perfect dominant-folder classification accuracy on the evaluated dataset while maintaining computational efficiency.

One of the key observations from the results is the **strong diagonal dominance** in the original–restored similarity matrix (Fig. 5(c)). This behavior indicates that local contour configurations captured by the 16-template mask are sufficiently distinctive to separate object classes even when global contour measures, such as length alone, produce ambiguous similarity scores. In contrast to length-only descriptors, which often yield overlapping distributions for geometrically complex shapes, the local template representation introduces discriminative information related to curvature transitions and directional changes.

The histogram of total matching counts (Fig. 1) reveals moderate variability across objects, reflecting differences in contour complexity and the number of local structural elements. Importantly, this variability does not compromise classification reliability, as each object preserves a dominant match. This suggests that the proposed descriptor is **robust to object-dependent geometric variation**, a desirable property for real-world inspection and recognition tasks.

The folder-wise aggregation analysis (Fig. 5(b)) further confirms the **absence of systematic bias** toward specific reconstructed datasets. Each reconstructed folder primarily accumulates matches from its corresponding original image, indicating that the matching strategy does not exploit reconstruction artifacts but instead relies on intrinsic contour geometry. This property is particularly relevant in industrial and technical vision applications, where acquisition and reconstruction conditions may vary.

From a computational perspective, the 16-template model represents a favorable trade-off between **descriptor richness and efficiency**. Compared to higher-dimensional template sets, the 16-template mask retains interpretability and low computational cost while providing sufficient discriminative power for the tested scenarios. This balance makes the method suitable for real-time or resource-constrained systems, where deep learning-based solutions may be impractical due to training data requirements and limited transparency.

Despite these advantages, several limitations should be acknowledged. First, the experiments were conducted on a relatively small dataset of planar binary objects. Although the results are promising, further validation on larger and more diverse datasets is required to assess scalability and generalization. Second, the method relies on accurate contour extraction; severe noise, contour fragmentation, or poor binarization may reduce the reliability of local template matching. Finally, while the 16-template representation resolves many ambiguities observed in global descriptors, extremely complex shapes with highly repetitive local patterns may still pose challenges.

Future work will focus on extending the proposed framework by incorporating **adaptive template weighting**, multi-scale contour analysis, and robustness evaluations under controlled noise and distortion conditions. Additionally, a systematic comparison with higher-dimensional template models and learning-based approaches will be conducted to further clarify the performance–complexity trade-offs.

6. Conclusion

This paper presented a **local contour-based representation using a 16-template mask** for the analysis and recognition of planar objects in binary images. The proposed approach was designed to overcome the limitations of global contour descriptors by incorporating local geometric configurations along object boundaries while preserving computational efficiency and interpretability.

Experimental results demonstrated that the 16-template contour mask achieves **100% dominant-folder classification accuracy** on the evaluated dataset. The strong diagonal dominance observed in the original–restored similarity matrix confirms that the proposed descriptor provides sufficient discriminative power to distinguish geometrically similar objects that cannot be reliably separated using contour length alone. Histogram and folder-wise analyses further showed that the method is stable across objects with varying contour complexity and does not introduce bias toward specific reconstruction sets.

From a practical perspective, the proposed method offers a favorable balance between **accuracy, robustness, and computational cost**. Unlike high-dimensional or learning-based descriptors, the 16-template model does not require extensive training data and maintains transparent geometric interpretation, making it well suited for real-time applications in technical vision, industrial inspection, defect analysis, and biomedical image processing.

Nevertheless, the current study is limited to planar binary objects and assumes reliable contour extraction. Future research will focus on extending the method to larger and more diverse datasets, evaluating robustness under severe noise and contour degradation, and exploring hybrid strategies that combine local template-based features with higher-level shape descriptors. Such extensions are expected to further enhance generalization capability while preserving the efficiency advantages of the proposed framework.

In summary, the results confirm that local contour template representations constitute an effective and practical alternative to purely global descriptors for shape recognition tasks, providing a solid foundation for further developments in contour-based image analysis.

References:

[1]. Gonzalez, R. C., & Woods, R. E. (2018). *Digital Image Processing* (4th ed.). Pearson. ISBN: 978-0133356724.

[2]. Sonka, M., Hlavac, V., & Boyle, R. (2014). *Image Processing, Analysis, and Machine Vision* (4th ed.). Cengage Learning. ISBN: 978-1133593607.

[3]. Freeman, H. (1974). Computer processing of line-drawing images. *ACM Computing Surveys*, 6(1), 57–97. https://doi.org/10.1145/356625.356627

[4]. Zahn, C. T., & Roskies, R. Z. (1972). Fourier descriptors for plane closed curves. *IEEE Transactions on Computers*, C-21(3), 269–281. https://doi.org/10.1109/TC.1972.5008949

[5]. Kuhl, F. P., & Giardina, C. R. (1982). Elliptic Fourier features of a closed contour. *Computer Graphics and Image Processing*, 18(3), 236–258. https://doi.org/10.1016/0146-664X(82)90034-X

[6]. Teh, C. H., & Chin, R. T. (1989). On the detection of dominant points on digital curves. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 11(8), 859–872. https://doi.org/10.1109/34.31447

[7]. Zernike, F. (1934). Beugungstheorie des Schneidenverfahrens. *Physica*, 1(7–12), 689–704. https://doi.org/10.1016/S0031-8914(34)80259-5

[8]. Flusser, J., Suk, T., & Zitová, B. (2009). *Moments and Moment Invariants in Pattern Recognition*. Wiley. ISBN: 978-0470699874.

[9]. Haralick, R. M., Sternberg, S. R., & Zhuang, X. (1987). Image analysis using mathematical morphology. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 9(4), 532–550. https://doi.org/10.1109/TPAMI.1987.4767941

[10]. Serra, J. (1982). *Image Analysis and Mathematical Morphology*. Academic Press. ISBN: 978-0126372403.

[11]. Canny, J. (1986). A computational approach to edge detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 8(6), 679–698. https://doi.org/10.1109/TPAMI.1986.4767851

[12]. Suzuki, S., & Abe, K. (1985). Topological structural analysis of digitized binary images by border following. *Computer Vision, Graphics, and Image Processing*, 30(1), 32–46. https://doi.org/10.1016/0734-189X(85)90016-7

[13]. Dalal, N., & Triggs, B. (2005). Histograms of oriented gradients for human detection. *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. https://doi.org/10.1109/CVPR.2005.177

[14]. Zhang, D., & Lu, G. (2004). Review of shape representation and description techniques. *Pattern Recognition*, 37(1), 1–19. https://doi.org/10.1016/j.patcog.2003.07.008

[15]. Mokhtarian, F., & Mackworth, A. (1992). Scale-based description and recognition of planar curves. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14(8), 789–805. https://doi.org/10.1109/34.149591

[16]. Samandarov, I. R., Manshurov, S. T., Dushatov, N. T., Miratoyev, Z. M., & Mustafin, R. R. (2023). Image processing in C++ using the OpenCV library. *Universum: Technical Sciences*, 5(110), 19–28.

[17]. Dmitry, S., Sadykov, S., Samandarov, I., Dushatov, N., & Miratoyev, Z. (2024). Method of investigation of stability and informativeness of basic and derivative features of microscopic and defectoscopic images of cast iron microstructure. *Universum: Technical Sciences*, 10(128), 31–39.