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Image Segmentation Techniques: An In-Depth Review and Analysis

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A B S T R A C T

In the fields of computer vision and image processing, image segmentation is a very important task. The image is partitioned into segments or regions then the visual data can be understood, analyzed and used easily. In this article, a comprehensive review of image segmentation methods is presented. It covers both the strengths and the advantages of some techniques as well as the weaknesses and limitations of other algorithms. The techniques used in image segmentation can be divided into four groups based on thresholding, region, edge and deep learning techniques. The fundamental principles, popularity of algorithms and evaluation metrics are mentioned. Also, the applications domains and future directions with current challenges are presented.

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1. Introduction

1.1. Background

In computer vision and image processing, image segmentation is very crucial because when image is divided into different regions, a better understanding is reached. There are many stages that can be included in image segmentation. Many disciplines involved the development of image segmentation such as medical image technology, autonomous cars, augmented reality and image search engine[1]. Image segmentation process requires partitioning an image into non-overlapping and meaningful regions. This is a necessary step for understanding of natural scenes[2]. Feature extraction and model are the main challenges after many years of efforts. Deep learning can be used in different stages. These stages include, collaborative, classic and semantic segmentation. there are algorithms and techniques related to each stage[2]. due to the diversity of human comprehension and uncertainty of visual perception, the representation of objects and important regions is a challenging task. There are innovative methods of image segmentation in deep neural network using different image datasets for more accurate results.

1.2. Importance of Image Segmentation in image processing and computer vision

Image segmentation is essential in many fields including image processing and computer vision. The image is segmented for better understanding. Medical imaging, object recognition and robotics represent crucial applications of image segmentation. Different techniques include edge-based, region-based, threshold-based and deep learning-based, all used wide ranging research for efficiency[3]. The aim of image segmentation is to gain better analysis by dividing images based on features like texture and color. This process is important to understand image in various areas.

1.3. Objectives of the Review

The purpose of this review is to evaluate and summarize image segmentation techniques and provide an overview of existing research related to this field. we mentioned the weaknesses and strengths of different studies as well as the need for advanced research if necessary. Furthermore, we identify and discuss limitations and gaps founded in some methods. This will help other researchers to figure out the useful techniques under different circumstances and find possible improvements[4].

2. Image segmentation methods

2.1. Thresholding-based Methods

Thresholding is one of the popular methods used in image segmentation because it is simple and easy to implement. Based on a threshold value, a given gray scale image is converted into binary image with two regions. The pixels that have gray level less than the threshold is classified as background while foreground represents the pixels with grey level greater than or equal the threshold, or vice versa. The pixels have only two values 0 and 1 and the result of image is binary image[5]. Therefore, to store pixel intensity, only one bit is needed.

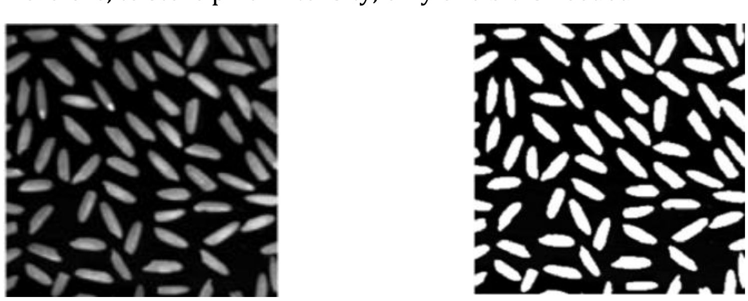


Fig. 1 - Thresholding segmentation[6]

2.1.1. Global Thresholding

Global thresholding is a method to convert grayscale image into binary image in image segmentation where a constant value (threshold T) is chosen and applied to the entire image. Since each pixel in the image is compared with this value, it is called global threshold. If the T value is greater than the pixel value then it is set to be zero and represent black. If the T value is less than or equal to the pixel value then it is set to be one and represent white.

The result is an image in a binary form where the background and foreground are clearly isolated. The consequence of segmentation is greatly affected by the value of the threshold T. In some cases, the value of T is initially estimated and then adjusted to enhance the segmentation. This technique is computationally efficient and simple; however, it may not be appropriate if the lighting conditions are varied or if the histogram of pixels intensity is not bimodal.

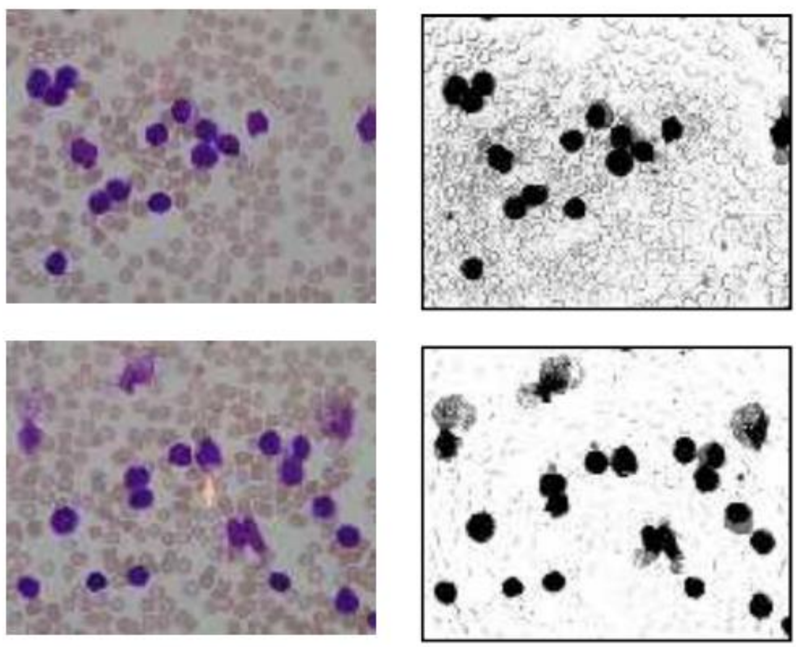
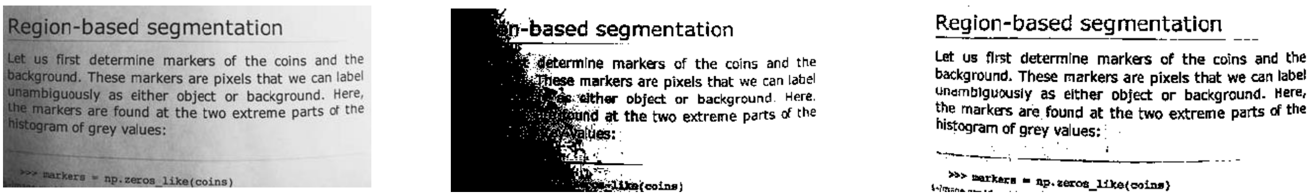


Fig. 2 – Global Thresholding[7]

2.1.2. Adaptive Thresholding

Adaptive thresholding is a very important method of image segmentation where threshold is dynamically adjusted based on the image contents. The threshold value is varied across the image according to the changes in noise, lighting and other factors[8]. This method is useful when the lighting of the image is varied. In global thresholding a single global value is used while in adaptive thresholding a threshold value is computed for each pixel depending on a small area around it. The threshold value of each pixel is calculated typically by using neighboring pixels intensities as a weighted sum. In mean adaptive thresholding, the weights are uniform whereas in gaussian adaptive thresholding, a gaussian distribution is followed[9].



Original image Global thresholding Adaptive thresholding

Fig. 3 – Adaptive Thresholding[10]

2.1.3. Multi-level Thresholding

Multi-level thresholding is a technique of image segmentation that expand the idea of binary thresholding[11], [12].Instead of separating the image into only two parts (background and foreground), multi-level thresholding partitions the image into multiple parts based on various thresholds[11], [12]Different threshold values (T1, T2, ..., Tn) are selected. These thresholds are compared with each pixel. If the intensity of pixel is less than T1 then it will be set to one. If this value lies between T1 and T2, it takes another value, and so on. The result is different regions representing the segmented image with multiple levels of intensity[11], [12].this can be especially convenient if there are more than two recognizable regions of interest in images.

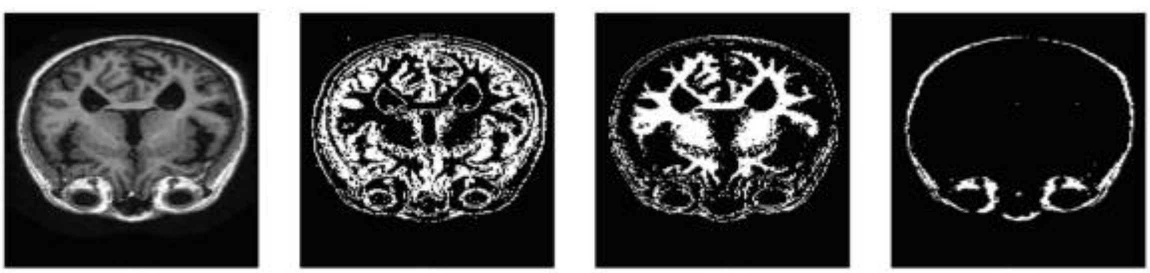


Fig. 4 – Multi-level Thresholding[13]

2.1.4. Limitations and Advancements

Thresholding-based segmentation methods which include (global thresholding, adaptive thresholding, and multilevel thresholding) are commonly used in image processing and computer vision because they are simple and easy, however; they have limitations.

- **Illumination changes sensitivity:** threshold-based techniques, specifically global thresholding, have illumination change sensitivity. A single global threshold cannot segment the image if there are variations in the lighting across the image[14], [15].

- **Assumption of distinct intensity distribution:** There is an assumption in these methods that the intensities of the background and foreground pixels work according to distinct distribution, however; this is not always true. In some cases, the foreground and background of the images have the same intensities, therefore the threshold methods fail to isolate them accurately[16].

- **Difficulty dealing with complex schemas:** in simple segmentation tasks, thresholding techniques can be efficient while it may encounter difficulties in more complicated scenarios such as multiple objects in in image, overlapping of the objects, or object variations in texture, size or shape[17].

2.2. Region-based Methods

Region based methods of image segmentation are approaches that divide the image into partitions that are similar based on predefined criteria. The aim is to segment the image into divisions that have a high correlation with the areas or objects of the real world of the image such that objects can be interpreted as a group of connected pixels that have similar properties.

2.2.1. Region growing

Region growing is considered a pixel-based image segmentation method that depends on the choosing of a seed point and adding the neighboring pixels to every seed point to build a region. In the beginning of the process, fixed pixels known as (seeds) are selected and work as a starting point for regions. Based on certain criteria like color or intensity, the surrounding pixels are added to each region after examination. If there are no more pixels to add to any region, then the process should be end[18]. Region growing algorithm is efficient when there are homogeneity and distinction in the image regions. However, the results can be significantly impacted by the similarity criterion and the choice of seeds.

2.2.2. Region Merging and Splitting

Region merging is a bottom-up image segmentation technique that include the process of gathering two or more neighboring region into one region based on specific criterion such as homogeneity[20]

It works as following:

- **Initial regions:** The process begins by structuring the initial region of the image.
- **Region adjacency graph (RAG):** A region adjacency graph is formed, which means the special relationship between regions of the image.
- **Merging:** the adjacent regions of each part are tested and considered to discover their similarity depending on specific criterion.

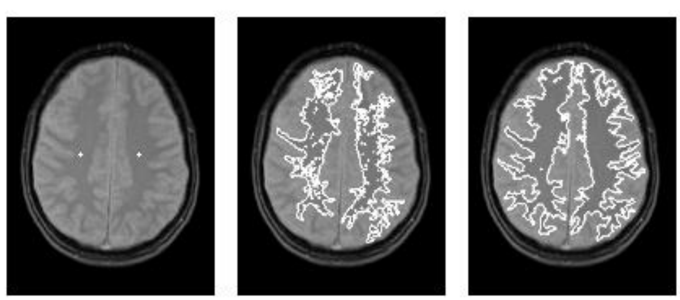


Fig. 5 – Region growing segmentation[19]

2.2.3. Watershed Transform

The watershed Transform is an image segmentation technique adopt the mathematical morphology. It is specifically beneficial for segmenting multiple objects in an image that are connecting each other[21].

It works as following:

- **Topographical interpretation:** The image is translated as a topographic landscape and the altitude represent the intensity of each pixel[22].

- **Flooding simulation:** From bottom up the landscape is flooding and the local minima in the image is filled with water[23].

- **Watershed Line Creation:** A watershed line is created to prevent objects from joining when the water rises and isolated bodies of water encountered[22].

- **Segmentation:** The watershed lines resulted from previous steps serve as segments' boundaries of the image.

A watershed transform is an efficient tool in image segmentation, however; over segmented outcomes may be produced because its sensitivity to the noise[21], [22].

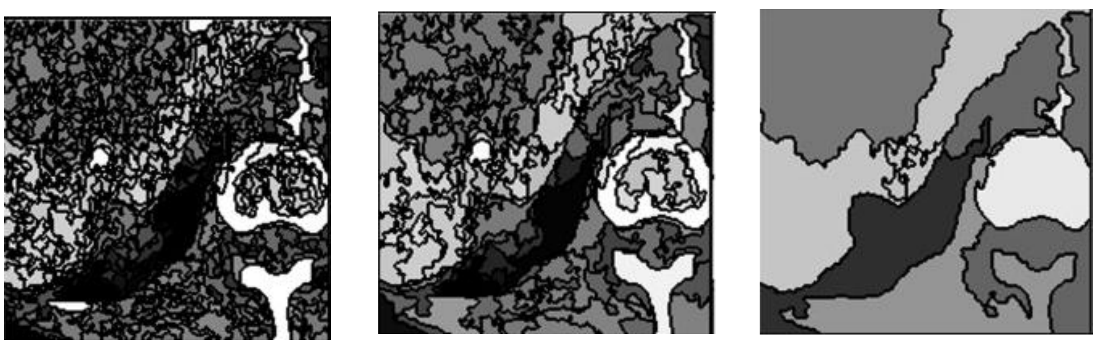


Fig. 6 – Watershed Segmentation[24]

2.2.4. Limitations and Advancements:

Region based segmentation methods are simple and efficient therefore they are extensively used in image processing. However, they may suffer from some limitations:

- **Initial seeds dependence:** The accuracy of segmentation is usually relying on the option of initial seed point[20].

- **Homogeneity Criterion:** The selecting of homogeneity criterion typically influences the result. If the criterion choice is not appropriate, the accuracy of segmentation may not match the true lines of regions.

- **Noise Sensitivity:** Region based methods have sensitivity to noise and this can lead to incorrect identification of regions and ignore the actual one.

In spite of these limitations, region-based segmentation methods have several advancements in recent years. These advancements include:

- **Integration with other techniques:** Region based method integrate with other techniques such as machine learning and edge detection[18]

- **Use of Advanced Algorithms:** State of the art algorithms are been developed such as region growing and seed selection to enhance the accuracy and efficiency of region-based segmentation algorithms.

- **Applications in Diverse Fields:** Region based segmentations methods are used in multiple fields like remote sensing, medical imaging and video surveillance[3].

2.3. Edge Based Methods

Edge based segmentation methods are techniques adopt in image processing that divide an image depend on sudden changes in intensity[25].These techniques work by discovering the edges of objects inside the image. The edge is interpreted as borderline between two sections with comparatively recognizable gray levels.

It works as following:

- **Edge detection:** To find the edges inside the image, many techniques can be used such as Prewitt, Sobel, Canny and Robert [26].
- **Edge linking:** after the edges have been detected they are connected together to form the objects' boundaries.

2.3.1. Gradient based methods:

Gradient based segmentation methods are technique in image segmentation that concentrate on detecting the boundaries of substances within an image by recognizing the areas where the gradient of intensity function is high in the image[28].

Its works as following:

- **Gradient Computation:** Some methods like Sobel, Prewitt and Ropert can be employed for calculating image intensity gradient.
- **Edge detection:** Edges represent places where there are acute changes in image intensity and gradient is high.
- **Edge Linking:** To complete the boundaries of an object, the detected edges are linked together.

Robert is considered as a simple gradient based edge detector where the gradient magnitude is computed by convolving with two (2x2) kernels

$$G_x = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}, \qquad G_y = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \qquad (1)$$

The gradient magnitude is given by:

$$Magnitude = \sqrt{G_x^2 + G_y^2} \qquad (2)$$

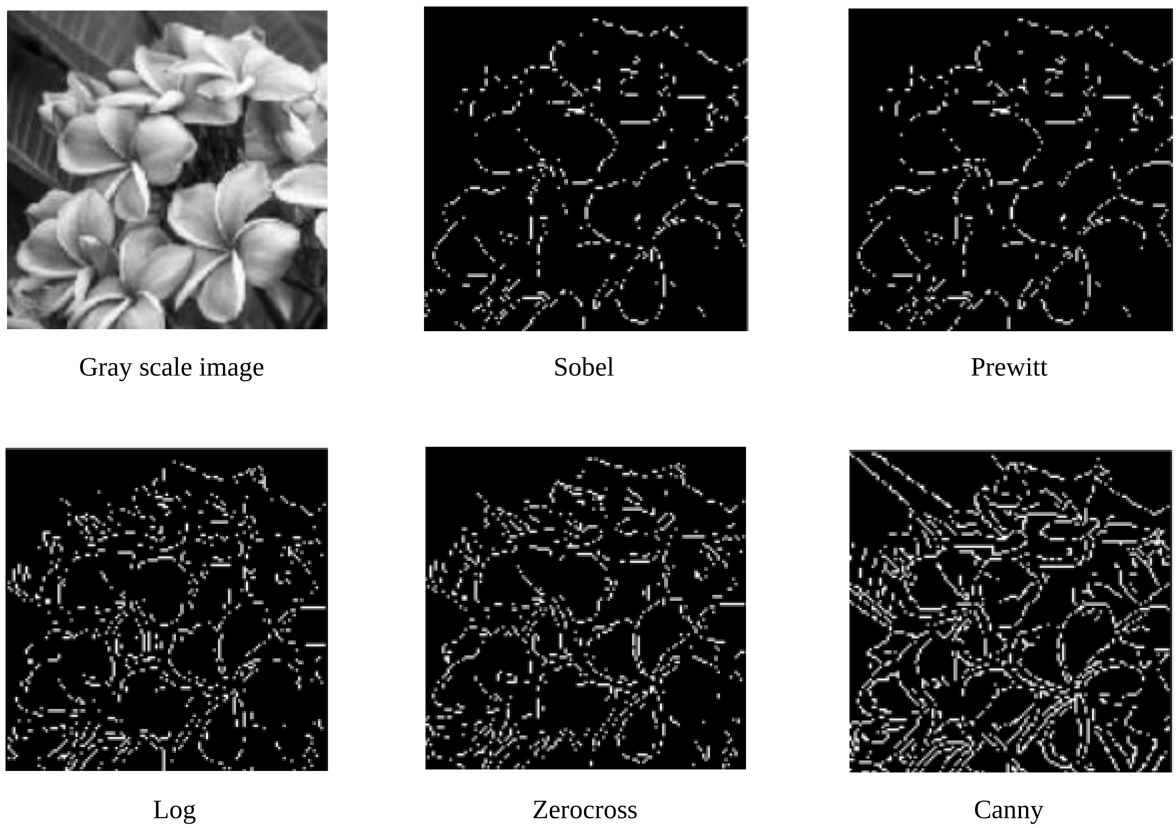


Fig. 7 – Edge based Segmentation[27]

Prewitt Operator also uses the gradient information to detects edges. It utilizes 3x3 convolution Kernel for both horizontal and vertical gradients

$$G_x = \begin{bmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{bmatrix}, \; G_y = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix} \qquad (3)$$

The Sobel operator uses large convolution kernels (3x3) to enhance edge detection and the gradients is calculated along both axis

$$G_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}, \; G_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \qquad (4)$$

The Laplacian operator distinguishes the zero crossing in the second derivative of the image directly. It involves the 3x3 kernel

$$Laplacian = \begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix} \qquad (5)$$

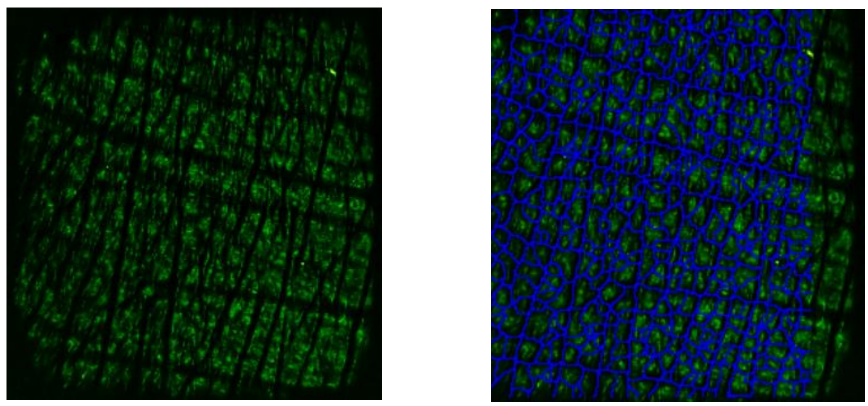


Fig. 8 – Gradient based segmentation[29]

2.3.2. Active Contour Models (Snakes):

Active contour Models, also called (Snakes) are a technique applied in image segmentation that requires the characterization of an object from a probably noisy 2D image[30].

Its works as following:

- Initialization: An initial contour is positioned around the border of the object.
- Energy Minimization: The contour repeatedly distorts and moves to towards the border of the object by reducing an energy function. This energy function is affected by restriction forces (internal energy) and the image forces (external energy)[30].
- Convergence: The process persists until the contour converges which happens when energy function attains its minimum value.

The sum of the external energy (the forces of image that shift the contour against object boundaries) and the internal energy (contour forces that confront the deformation) represents the snake energy function. Many applications use active contour model such as segmentation, stereo matching, edge detection, object tracking, shape recognition[30].However, they need familiarity of the desired contour shape ahead.

The internal energy is given by the following equation:

$$E_{int} = \int (\alpha \mid \nabla C \mid^2 + \beta \mid \nabla^2 C \mid^2) \, dA \qquad (6)$$

where:

- C represents the contour.
- ∇C is the gradient of the contour.
- ∇2C is the Laplacian of the contour.
- α and β are positive constants controlling the trade-off between curvature and length regularization.

While the external energy is given as follow:

$$E_{ext} = \int g(\mathbf{x}) \mid \nabla I(\mathbf{x}) \mid dA \qquad (7)$$

where:

- I(x) is the image intensity at position x.
- g(x) is a weighting function that emphasizes relevant image features.

The total energy combines internal and external energies:

$$E_{total} = E_{int} + E_{ext} \qquad (8)$$

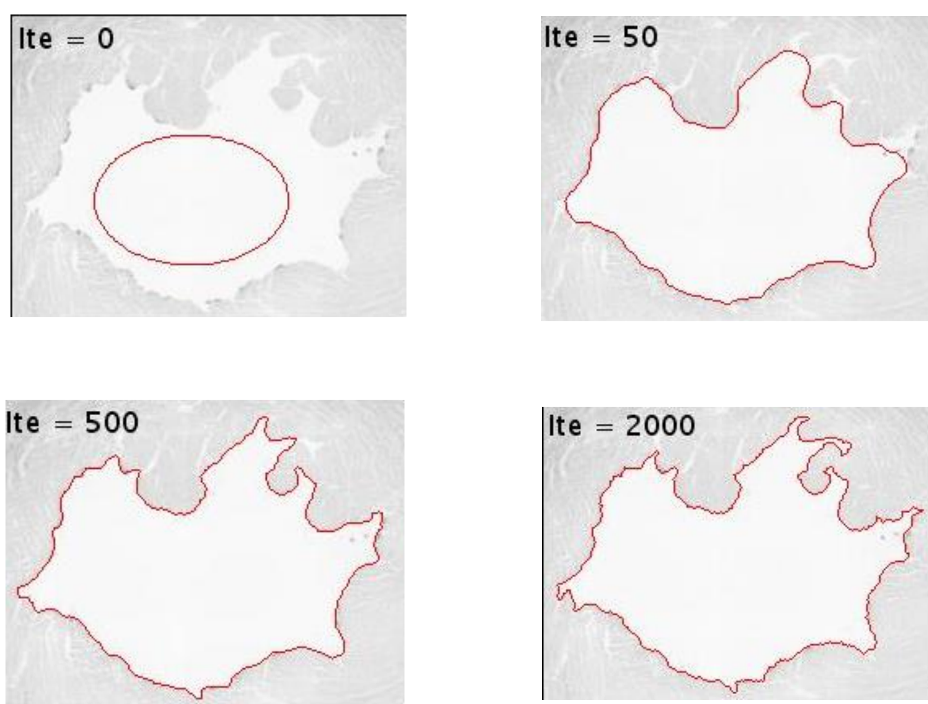


Fig. 9 –Active contour segmentation

2.3.3. Limitations and Advancements:

Although edge-based methods are used widely in image segmentation, they have some limitations.

- **Sensitivity to Noise:** Edge based segmentation approaches are very sensitive to noise. The existence of noise can cause incorrect detection of edges and make it hard to find the true edges.

- **Difficulty with weak edges:** These techniques possibly fail to find weak or faint edges. If different regions of an image have low contrast between them, edge detections models may be identified the boundaries inaccurately [31].

- **Dependence on threshold selection:** The efficiency of edge detections models can generally rely on the appropriate threshold selection. Unsuitably selected thresholds can result in lost edges or detection of wrong edges.

In spite of these limitations, there have been substantial advancements in edge-based segmentation methods:

- **Robust Edge Detection Algorithms:** There is a new development in the algorithms of robust edge detection such as the Modified Moor-Neighbor tracing algorithm which is proposed as robust edge detection techniques[32].

- **Integration with other techniques:** The integration between edge-based methods and other techniques has enhance segmentation result. For example, the integration between seeded region grown and color edge extraction has shown an improvement in automatic image segmentation[31].

- **Use of Machine Learning:** Machine learning models have been employed to edge detection to increase the robustness and the accuracy of edge-based segmentation. For instance, the use of deep learning techniques to learn and predict edges in complicated images[33].

2.4. Cluster Based Methods

Cluster based segmentation methods are procedures that gather identical data points together depend on specific characteristics.

- **Hierarchal Clustering:** In this type of clustering, a tree of clusters is created. Hierarchal clustering clusters the data point into multiple groups and creates a hierarchy of clusters therefore it called hierarchal clustering[34].

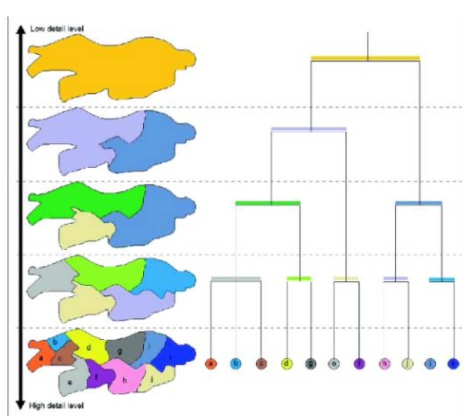
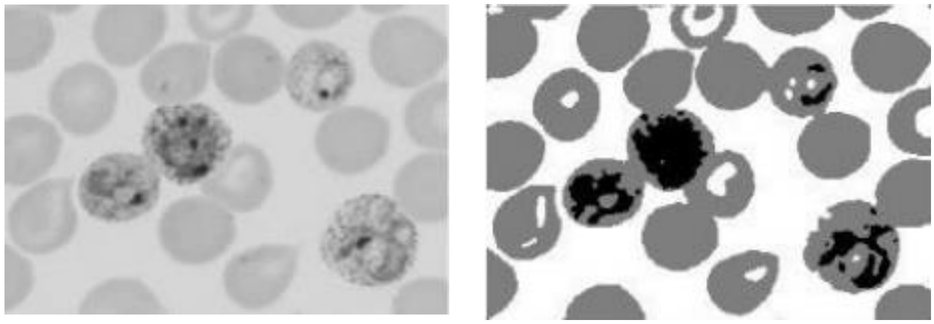


Fig. 10 – Hierarchal Clustering Segmentation [35]

- **Partitional Clustering:** The data points are divided into non-overlapping clusters and there is no structure or order to them. One of the popular techniques of partitional clustering is K-means[34].



Original image segmented image

Fig. 11 –k-means Clustering Segmentation [36]

- **Density-Based Clustering:** In this method, clusters are defined as spaces that have intensity higher than the rest of the data set. Objects in scattered areas are generally represent noise or border points. One of the popular methods of Density-Based Clustering is DBSCAN[37].

Original image segmented image

Fig. 12 –Density-Based Clustering Segmentation [38]

- **Grid-Based Clustering:** this technique quantizes the space of data into finite cells number that construct grid structure. All clustering processes are done on cells or grid[34].

- **Model-Based Clustering:** These methods try to optimize the fit between some mathematical models and data. Such procedures often adopt the concept of generation data by a mixture of underling probability distribution[34]

The methods that adopt cluster-based segmentation are used widely in image processing because of their efficiency in gathering similar pixels together, but these methods may encounter some limitations:

- **Initial Cluster Dependence:** the initial clusters play an important role in the quality of segmentation; Therefore, poor segmentation results come from poorly chosen initial clusters[39].

- **Assumption of Cluster Shape:** Several clustering algorithms consider that the clusters are convex and isotropic, which can be different from the real-world images[39].
- **Difficulty Determining the Number of Clusters:** The number of clusters should be designate in many algorithms and it cannot be easy to specify in a given image[39].
- **Sensitivity to Noise and Outliers:** Clustering algorithms may be high responsive to outliers and noise; therefore, the quality of segmentation can be affected.

Despite these limitations, clustering based algorithms have many significant advancements:

- **Development of Robust Clustering Algorithms:** New algorithms that are more robust to outliers and noise have been developed. As a result, clusters that have different shapes and sizes can be handled effectively.
- **Use of super pixels:** To reduce the complicated of image processing, superpixels may be used to represent features instead of pixels[2].
- **Integration with Other Techniques:** To improve the segmentation quality, clustering based segmentation methods can be integrated with other techniques[2].

2.5. Deep Learning Based Methods

The neural networks are utilized to automatically segment an image into meaningful partitions or regions. These methods are very popular because of its effectiveness in many tasks such as object detections, scene understanding and medical image analysis[40]. Here are some segmentation methods that are deep learning based.

2.5.1. Semantic segmentation

In semantic segmentation, each pixel in an image is labelled with corresponding class label. The image is divided into sections depending on semantic meaning. This type of segmentation usually used in projects such as objects detection, autonomous driving and scene understanding. One of the revolutionary architectures for semantic segmentation is Fully Convolutional Network (FCNs) where pixel-wise class labels are predicted through the network by swapping fully connected layers with convolutional layers. U-Net is another popular construction for biomedical image segmentation where contracting path is established to catch context and a symmetric expanding path to allow precise localization[41].

2.5.2. Instance Segmentation:

This method includes not only marking each pixel with a class but also discriminating between individual instances of the correspondent class. This is necessary for tasks where accurate delineation of objects is needed.

Mask R-CNN expand the Faster R-CNN architecture where a branch is added alongside existing branch to predict segmentation masks for object detection. The object instances can be identified and segmented accurately[43].YOLACT is an instance segmentation which represents a one stage method and completes a real time performance. The prediction of masks is achieved directly at multiple scales of feature maps via as set of lightweight prediction modules[44].

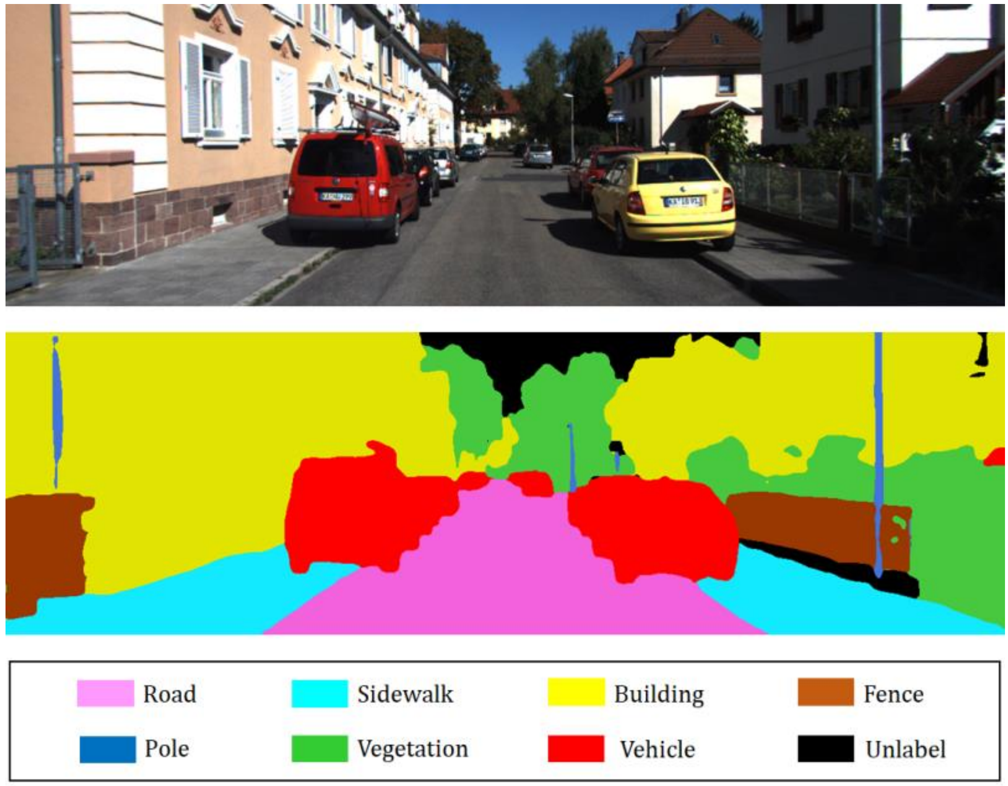


Fig. 13 –Semantic Segmentation[42]

Fig. 14 –Semantic Segmentation[45]

2.5.3. Panoptic Segmentation

This technique intends to combine the tasks of instance segmentation and semantic segmentation into one framework, providing an entire knowledge of visual scene where every pixel is labeled with a category label and the individual instances are differentiated[46].

Panoptic FPN expands the feature pyramid network to accomplish instance and semantic segmentation simultaneously. It merges the predictions of semantic segmentation from the backbone network with the predictions of instance segmentation from a different branch[46]. BlendMask is a modern technique of panoptic segmentation that exploits a hybrid architecture that merges center-based detection and instance segmentation.

2.5.4. Boundary Detection

These methods concentrate on determining the borderlines of the object with an image. Although not exactly a segmentation, they provide necessary information for tasks like shape analysis, object tracking image segmentation[47].

DeepLap is a series architectures of convolutional neural network created for semantic image segmentation. It integrates atrous convolution (dilated convolution) to grab object boundaries and details[48].

Holistically-Nested Edge Detection (HED) is a technique based on deep learning that predict directly pixel level object boundaries where a detailed boundary map is produced by using a holistic image training method[49].

2.5.5. Limitations and Advancements

Deep learning segmentation methods have accomplished a very important improvement on the field of image segmentation, however there are some limitations

- **Computational cost:** Deep learning segmentations models that are used in image segmentation require a high computational cost because of the large numbers of parameters[50].

- **Overfitting:** Deep learning models suffer from overfitting to the learning data, where it can work well on training data but fail on real data.

- **Lack on interpretability:** The models of deep learning often called "black boxes" because it is not easy to understand why they give definite predictions[50].

- **Dependance on data quality:** The achievements of deep learning models rely on the quality of the training data. If the training data contains errors or it is noisy, the performance of model will give unacceptable result[51].

Although there have been some limitations, deep learning-based segmentation methods have important advancements.

- **Developments of New Architectures:** New models of networks have been developed especially for image segmentation such as Mask R-CNN and U-Net[52].

- **Use of transfer learning:** In transfer learning, a model trained on one task can be adopted on another task. This approach is used to reduce the volume of labeled data.

- **Integration with other techniques:** Deep learning techniques are being integrated with other methods such as region growing and edge detection to enhance the segmentation result [51].

3. Evaluation Metrics

Evaluation metrics of image segmentation give a quantitative measure to estimate the accuracy of image segmentation algorithms. Some of the common metrics are:

- **Pixel accuracy:** this metric is very simple and measure the percentage of correctly classified pixels. If we denote the number of pixels that classified correctly as

$$N_{correct}$$

and the total number of pixels as

$$N_{total}$$

Then the pixel accuracy is given by

$$Pixel\ Accuracy = \frac{N_{correct}}{N_{total}} \qquad (9)$$

Intersection Over Union (IoU): This metric known as Jaccard index and measure the overlap between the ground truth and the predicted segmentation. If the area of overlap is denoted as

$$A_{overlap}$$

and the total area of union as

$$A_{union}$$

Then IoU is:

$$IoU = \frac{A_{overlap}}{A_{uion}} \qquad (10)$$

- **Dice Coefficient:** This metric also known as Dice similarity coefficient (DSC) or F1 score where the overlap between the predicted segmentation and ground truth is measured, if we denote the area of the area of overlap as

$$A_{overlap}$$

and the total area of predicted and ground truth segmentation as

$$A_{predicted}$$

and $$A_{groundtruth}$$

respectively then the Dice Coefficient is found by:

$$Dice\ Coefficient = \frac{2 \times |A\_overlap|}{|A\_predicted| + |A\_groundtruth|} \qquad (11)$$

- **Precision and Recall:** these two metrics are used in measuring the accuracy of image segmentation models. They are appropriate especially in cases when classes are unbalanced[53] .In the fields of image segmentation, precision is the ratio of truly positive pixels that predicted as positive. It measures the performance of positive predictions. It is been calculated as:

$$P = \frac{TP}{TP + FP} \qquad (12)$$

Where:

- ○ TP (True Positive) is the number of identified pixels as positive and they are originally positive.
- ○ FP (False Positive) is the number of incorrectly identified pixels as positive and they are originally negative.

- Recall or sensitivity: is the ratio of the correctly identified pixels which is actually positive pixels. It finds the ability of the model to choose all positive pixels. It is calculated as:

$$R = \frac{TP}{TP + FN} \qquad (13)$$

Where:

- ○ FN (False Negative) is number of pixels wrongly identified as negative and it is actually positive pixels.

4. Conclusion

In conclusion, the techniques of image segmentation have evolved essentially in the course of time. For each method, there are challenges and advantages. Classical methods such as region growing, edge detection and thresholding provide a firm basis, but they often can encounter some difficulties dealing with complex images and may fail to achieve the flexibility of modern approaches. Machine learning and deep learning-based segmentation techniques such as CNNs represent the revolution in the field of image segmentation and provide very powerful tools in terms of efficiency and accuracy particularly in complicated tasks like instance and semantic segmentation. However, they demand significant amount of annotated data and considerable computational resources. Hybrid techniques that combine the machine learning with traditional methods are rising as encouraging solutions to influence the power of both worlds. Their object is to accomplish high accuracy while reducing the reliance on extensive annotated data. In spite of the progress, some challenges persist. These challenges include segmenting images that have low contrast, manipulating noise, and dealing with distinctions in size, shape, and texture of the objects of interest. Moreover, the interpretability of deep learning models is still an important concern. The focus of future research in the field of image segmentation will try to address the challenges and build new efficient algorithms, as well as enhancing the interpretability of deep learning models and study the semi-supervised and unsupervised learning techniques to reduce the necessity of annotated data. In summary, image segmentation still a very sophisticated and critical area in the new research of image processing and computer vision with wide range of applications from autonomous vehicles to medical imaging. The continuous progression in this field is expected to open new opportunities and change many industries.

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