Efficient Semantic Segmentation for Autonomous Vehicles with Limited Computational Resources

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Abstract—The abstract goes here.

Index Terms—Computer Society, Computer Vision and Pattern Recognition

1 Introduction

Semantic segmentation, which involves classifying each pixel in an image into a set of predefined categories, is a fundamental task in computer vision, and has a crucial role in autonomous driving systems to enable the vehicle to understand and interpret its surroundings. Dividing the image into multiple semantic regions is a key step in the perception pipeline of autonomous vehicles, as it provides a rich representation of the environment identifying the instances of objects and their relations.

Autonomous vehicles operate in a wide range of environments, and thus, the real-time performance of the segmentation algorithm is critical as it's a key component required for safe and reliable decision-making. However, the computational resources available in autonomous vehicles are often limited due to physical constraints including memory capacity due to existence of large models and processing speed required for real-time responses. These limitations pose significant challenges for implementing efficient and accurate semantic segmentation algorithms on autonomous vehicles, as traditional methods typically rely on computationally expensive deep neural networks with many parameters.

In addition, complex scenes, very often contain many instances and abstract levels, and high-resolution images to capture fine-grained details, pose additional challenges for semantic segmentation algorithms. **Complex scenes** require the model to classify numerous objects accurately, even more if the model request some hierarchical information. However, achieving high accuracy in semantic segmentation is a challenging task due to presence of occlusions, object overlaps and lighting variations, which can lead to inaccurate classification. **High-resolution** of the input images increase the computational demands of semantic segmentation models, which can lead to a significant drop in performance, making it difficult to achieve real-time processing required by autonomous vehicles.

The objective is to enable real-time semantic segmentation on autonomous vehicles without compromising the model accuracy while keeping the computational requirements low. Also, should be able to handle different levels of scene detail and adapt to different driving scenarios, due to dynamic and changing environments.

To evaluate the proposed approach, made use of benchmark datasets(*i.e.* Cityscapes [1], Mapillary Vistas [2]) for semantic segmentation in autonomous driving scenarios. This paper findings have important implications for the development of *practical* semantic segmentation algorithms for autonomous vehicles, deploying embedded systems with constrained computational resources, in order to contribute to the advancement of safe and reliable autonomous driving systems.

2 Theorical Foundations

2.1 Fundamentals of Semantic Segmentation

2.1.1 Image Segmentation

Segmentation is the process of breaking an image into groups of similar pixels [3], dividing the image into segments. The goal of segmentation is to simplify the representation of an image into something that is more *meaningful*, allowing more detailed analysis to be performed on each segment. There are two ways to approach the problem of segmentation: *detecting boundaries* or *detecting regions* [3].

Boundary detection involves finding the boundaries between regions, using techniques such as edge detection with the Canny algorithm [4] or thresholding with the Otsu algorithm [5]. **Region detection** involves finding regions of similar pixels, using techniques such as clustering with the K-means algorithm [6] or the Mean-Shift algorithm [7]. Figure

1 shows an example of image segmentation using both boundary detection and region detection.

Figure 1: Image Segmentation using boundary and region detection [3]

2.2 Ground Truth

Ground Truth in the context of semantic segmentation refers to the *correct* segmentation of an image, manually annotated as segmentation masks that define the boundaries of the objects in the image [3]. The ground truth is used to train, validate and test semantic segmentation models. Pixel-level ground truth is the most common type of ground truth used in semantic segmentation datasets, where each pixel is assigned a label that defines the object it belongs. Figure 2 and 3 shows examples of pixel-level ground truth.

2.2.1 Cityscapes Dataset

Cityscapes is a dataset for semantic urban scene understanding, containing 5000 high quality pixel-level ground truth images, with 30 classes of objects [1]. Figure 2 shows an example of a Cityscapes image and its corresponding pixel-level ground truth. Dataset offers three different splits: *train*, *validation* and *test*. As its used for numerous semantic segmentation models, it seems to be the most balanced dataset in terms of classes distribution. Also, having some hierarchy between classes, it is possible to group them into 8 upper classes.

Figure 2: Cityscapes semantic segmentation

2.2.2 KITTI Dataset

KITTI is a dataset for autonomous driving, containing 200 pixel-level ground truth images, with 34 classes of objects [8]. Figure 3 shows an example of a Kitti image and its corresponding pixel-level ground truth. Dataset offers two different splits: *train* and *test*. As its used for autonomous driving, it seems to be the most unbalanced dataset in terms of classes distribution. Also, having no hierarchy between classes, it is not possible to group them into upper classes.

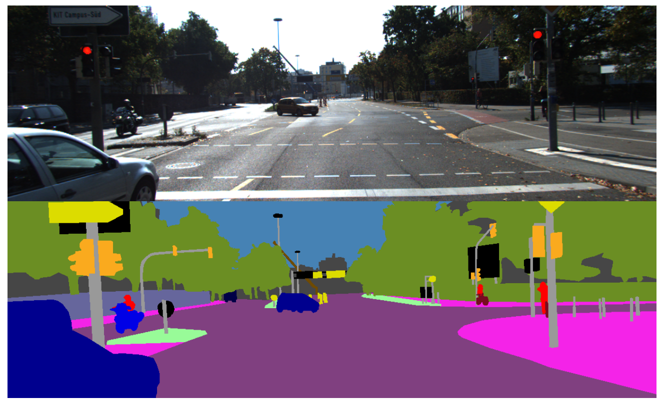

Figure 3: Kitti semantic segmentation

2.3 Evaluation Metrics

2.3.1 Pixel Accuracy

Pixel Accuracy (PA) is the simplest metric used to evaluate the performance of a semantic segmentation model. It is calculated by cumputing the ratio between the number of correctly classified pixels and the total number of pixels in the image [9]. The pixel accuracy is a value between 0 and 1, with 1 being the best possible score.

$$PA = \frac{TP_i + TN_i}{TP_i + TN_i + FP_i + FN_i} \tag{1}$$

where TP_i is the number of true positives (correct *foreground pixels*), TN_i is the number of true negatives (correct *background pixels*) meaning correctly classified pixels, FP_i is the number of false positives (incorrect *foreground pixels*) and FN_i is the number of false negatives (incorrect *background pixels*) meaning incorrectly classified pixels.

Although the pixel accuracy is a simple metric, it is not a good metric to evaluate the performance of a semantic segmentation model. This is because the pixel accuracy does not take into account the *class imbalance problem*, presented in semantic segmentation datasets and real world scenarios.

2.3.2 Mean Pixel Accuracy

Mean Pixel Accuracy (mPA) calculate the pixel accuracy(*PA*) for each semantic category and then averages the results [9]. The mPA is a value between 0 and 1, with 1 being the best possible score.

$$mPA = \frac{1}{n}\sum_{i=1}^{n} PA_i \tag{2}$$

using the same variables as in equation 1 and n is the number of semantic categories. However, the mPA still does not take into account the *class imbalance problem*.

2.3.3 Intersection over Union

Intersection over Union (IoU) or *Jaccard index* is calculated by dividing the intersection of the predicted segmentation and the ground truth segmentation by the union of the predicted segmentation and the ground truth segmentation [9]. The IoU is a value between 0 and 1, with 1 being the best possible score.

$$IoU = \frac{|A \cap B|}{|A \cup B|} = \frac{TP_i}{TP_i + FP_i + FN_i} \tag{3}$$

where A is the predicted segmentation, B is the ground truth segmentation, $|A \cap B|$ represents the *overlapping area* between A and B meaning correctly classified pixels as foreground. While $|A \cup B|$ represents the *union area* between A and B meaning all pixels in foreground.

It is a useful metric to evaluate the performance of a semantic segmentation when the *class imbalance problem* is present, take into account the presence of small objects and penalize false positives. However, the IoU is still not a good metric alone to measure the performance of instance segmentation models, because it does not evaluate the background accuracy.

2.3.4 Mean Intersection over Union

Mean Intersection over Union (mIoU) calculate the IoU for each semantic category and then averages the results [9]. The mIoU is a value between 0 and 1, with 1 being the best possible score.

$$mIoU = \frac{1}{n}\sum_{i=1}^{n} IoU_i \tag{4}$$

using the same variables as in equation 3 and n is the number of semantic categories. The mIoU is a good metric to evaluate the performance of a semantic segmentation model, but it still does not evaluate the background accuracy.

2.3.5 Frecuency Weighted Intersection over Union

Frecuency Weighted Intersection over Union (FWIoU) extends the mIoU metric by taking into account the *class imbalance problem* by assigning a weight to each semantic category based on the number of pixels in the ground truth. This means that the FWIoU penalizes more the incorrect classification of pixels in semantic categories with more pixels in the ground truth, providing a more balanced evaluation [9], [10]. The FWIoU is a value between 0 and 1, with 1 being the best possible score.

$$FWIoU = \frac{1}{\sum_{i=1}^{n}|B_i|}\sum_{i=1}^{n}|B_i| IoU_i \tag{5}$$

where $|B_i|$ is the number of pixels in the ground truth for the semantic category i (*frequency*) and n is the number of semantic categories.

2.4 Fundamentals of Convolutional Neural Networks

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2.4.1 Convolutions

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2.4.2 Pooling

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2.4.3 Fully Connected Layers

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2.4.4 Skip Connections

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2.4.5 Activation Functions

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2.5 Fundamentals of Transformers

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2.5.1 Backbone

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2.5.2 Encoder

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2.5.3 Decoder

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3 Related Work

3.1 Handcrafted

3.1.1 Thresholding

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3.1.2 Region-based

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3.1.3 Clustering

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4 Techniques

4.1 ENet [11]

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4.2 ESPNet [12]

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4.3 FPN [13]

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