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ABSTRACT

Semantic image segmentation (SiS) plays a fundamental role in a broad variety of computer vision applications, providing key information for the global understanding of an image. This survey is an effort to summarize two decades of research in the field of SiS, where we propose a literature review of solutions starting from early historical methods followed by an overview of more recent deep learning methods including the latest trend of using transformers. We complement the review by discussing particular cases of the weak supervision and side machine learning techniques that can be used to improve the semantic segmentation such as curriculum, incremental or self-supervised learning.

State-of-the-art SiS models rely on a large amount of annotated samples, which are more expensive to obtain than labels for tasks such as image classification. Since unlabeled data is instead significantly cheaper to obtain, it is not surprising that Unsupervised Domain Adaptation (UDA) reached a broad success within the semantic segmentation community. Therefore, a second core contribution of this monograph is to summarize five years of a rapidly growing

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field, Domain Adaptation for Semantic Image Segmentation (DASiS) which embraces the importance of semantic segmentation itself and a critical need of adapting segmentation models to new environments. In addition to providing a comprehensive survey on DASiS techniques, we unveil also newer trends such as multi-domain learning, domain generalization, domain incremental learning, test-time adaptation and source-free domain adaptation. Finally, we conclude this survey by describing datasets and benchmarks most widely used in SiS and DASiS and briefly discuss related tasks such as instance and panoptic image segmentation, as well as applications such as medical image segmentation.

We hope that this monograph will provide researchers across academia and industry with a comprehensive reference guide and will help them in fostering new research directions in the field.

Preface

Semantic image segmentation (SiS) plays a fundamental role towards a general understanding of the image content and context. In concrete terms, the goal is to label image pixels with the corresponding semantic classes and to provide boundaries of the class objects, easing the understanding of object appearances and the spatial relationships between them. Therefore, it represents an important task towards the design of artificial intelligent systems. Indeed, systems such as intelligent robots or autonomous cars should have the ability to coherently understand visual scenes, in order to perceive and reason about the environment holistically.

Hence, semantic scene understanding is a key element of advanced driving assistance systems (ADAS) and autonomous driving (AD) (Teichmann *et al.*, 2018; Hofmarcher *et al.*, 2019) as well as robot navigation (Zurbrügg *et al.*, 2022). The information derived from visual signals is generally combined with other sensors such as radar and/or LiDAR to increase the robustness of the artificial agent's perception of the world (Yurtsever *et al.*, 2020). Semantic segmentation fuels applications in the fields of robotic control and task learning (Fang *et al.*, 2018; Hong *et al.*, 2018b), medical image analysis (see Section 4.3), augmented reality (DeChicchis, 2020; Turkmen, 2019), satellite imaging (Ma *et al.*, 2019) and many others.

The growth of interest in these topics has also been caused by recent advances in deep learning, which allowed a significant performance boost in many computer vision tasks – including semantic image segmentation. Understanding a scene at the semantic level has long been a major topic in computer vision, but only recent progress in the field has allowed machine learning systems to be robust enough to be integrated into real-world applications.

The success of deep learning methods typically depends on the availability of large amounts of annotated training data, but manual annotation of images with pixel-wise semantic labels is an extremely tedious and time consuming process. As the major bottleneck in SiS is the high cost of manual annotation, many methods rely on graphics platforms and game engines to generate synthetic data and use them to train segmentation models. The main advantage of such synthetic rendering pipelines is that they can produce a virtually unlimited amount of labeled data. Due to the constantly increasing photo-realism of the rendered datasets, the models trained on them yield good performance when tested on real data. Furthermore, they allow to easily diversify data generation, simulating various environments and weather/seasonal conditions, making such data generation pipeline suitable to support the design and training of SiS models for the real world.

While modern SiS models trained on such simulated images can already perform relatively well on real images, their performance can be further improved by domain adaptation (DA) – and even with *unsupervised domain adaptation* (UDA) not requiring any target labels. This is due to the fact that DA allows to bridge the gap caused by the *domain shift* between the synthetic and real images. For the aforementioned reasons, sim-to-real adaptation represents one of the leading benchmarks to assess the effectiveness of *domain adaptation for semantic image segmentation* (DASiS).

The aim of our monograph is to overview the research field of SiS. On the one hand, we propose a literature review of semantic image segmentation solutions designed in the last two decades – including early historical methods and more recent deep learning ones, also covering the recent trend of using transformers with attention mechanism. On the other hand, we devote a large part of the monograph to survey methods

designed *ad hoc* for DASiS. While our work shares some similarities with some of the previous surveys on this topic, it covers a broader set of DASiS approaches and departs from these previous attempts pursuing different directions that are detailed below.

Amongst the existing works surveying SiS methods, we can mention Thoma (2016) who gives a brief overview of some of the early semantic segmentation and low-level segmentation methods. Li *et al.* (2018a) and Zhou *et al.* (2018) discuss some of the early deep learning-based solutions for SiS. A more complete survey on deep SiS models has been proposed by Minaee *et al.* (2020), while Zhang *et al.* (2020a) focus on reviewing semi- and weakly supervised semantic segmentation models. We cover most of these methods in Section 1, where we provide a larger spectrum of the traditional SiS methods in Section 1.1. Then, in Section 1.2, we organize the deep SiS methods according to their *most important characteristics*, such as the type of encoder/decoder, attention or pooling layers, solutions to reinforcing local and global consistency. In contrast to the previous surveys, this section also includes the latest SiS models that use attention mechanisms and transformers as encoder and/or decoder. One of the core contributions of this section is Table 2.1, which presents a broad set of deep models proposed in the literature, and summarized according to the above mentioned characteristics. Finally, in Section 1.3 we review not only semi- and weakly supervised SiS solutions, but also new trends whose goal is improving semantic segmentation, such as curriculum learning, incremental learning and self-supervised learning.

In Section 2, we present and categorize a large number of approaches devised to tackle the DASiS task. Note that previous DA surveys (Gopalan *et al.*, 2015; Csurka, 2017; Kouw and Loog, 2021; Zhang and Gao, 2019; Venkateswara and Panchanathan, 2020; Singh *et al.*, 2020; Csurka, 2020; Wang and Deng, 2018; Wilson and Cook, 2020) address generic domain adaptation approaches that mainly cover image classification and mention only a few adaptation methods for SiS. Similarly, in recent surveys on domain generalization (Wang *et al.*, 2020b; Zhou *et al.*, 2020a), online learning (Hoi *et al.*, 2018) and robot perception (Garg *et al.*, 2020), several DA solutions are mentioned, but yet DASiS received only marginal attention here. The most complete survey – and therefore most similar to the content of our Section 2 –

is by Toldo *et al.* (2020a), which also aimed at reviewing the recent trends and advances developed for DASiS. Nevertheless, we argue that our survey extends and enriches it in multiple ways. First, our survey is more recent in such a quickly evolving field as DASiS, so we address an important set of recent works appeared after their survey. Second, while we organize the DASiS methods according to how domain alignment is achieved similarly to (Toldo *et al.*, 2020a) – namely on *image, feature or output level* – we complement it with different ways of grouping DASiS approaches, namely based on their most important *characteristics*, such as the backbone used for the segmentation network, the type and levels of domain alignments, any complementary techniques used and finally the particularity of each method compared to the others. We report our schema in Table 2.1, which represents one of the core contributions of this monograph. Third, we survey a large set of complementary techniques in Section 2.3 that can help boost the adaptation performance, such as self-training, co-training, self-ensembling and model distillation.

Finally, in Section 2.4 we propose a detailed categorization of some of the *related DA tasks* – such as multi-source, multi-target domain adaptation, domain generalization, source-free adaptation, domain incremental learning, etc. – and survey solutions proposed in the literature to address them. None of the previous surveys has such a comprehensive survey on these related DA tasks, especially what concerns semantic image segmentation.

To complement the above two sections, which represent the core contributions of our monograph, we further provide in Section 3 a list of the datasets and benchmarks typically used to evaluate SiS and DASiS methods, covering the main metrics and discuss different SiS and DASiS evaluation protocols. Furthermore, in Section 4 we propose a short overview of the literature for three tasks strongly related to SiS, namely instance segmentation in Section 4.1, panoptic segmentation in Section 4.2 and medical image segmentation in Section 4.3.

We hope that our monograph, with its comprehensive survey of the main trends in the field of semantic image segmentation, will provide researchers both across academia and in the industry with a solid basis and background to help them develop new methods and foster new research directions.

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