3D Plant Segmentation for High Throughput Phenotyping using 3D Morphological Algorithms

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Introduction: In recent years digital phenotyping has become the main tool plant researchers use to study and breed new plant strains that are robust against climate conditions such as drought. A novel and viable approach for digital plant phenotyping is top-view laser scanning, which ensures high throughput and allows the extraction of precise plant phenotype describing measurements. A present unsolved problem in high-throughput and high-precision phenotyping is the automated plant organ segmentation from 3D scan data into semantic parts. Solving this problem can enable plant understanding/phenotyping and consequently enhance plant research. Even though, the current approaches in the literature for 3D plant scan segmentation can yield accurate segmentation of the scans [2, 3, 4, 7, 10], they are limited either because they are specialised on certain plants [3, 4], or, in the case of deep learning based methods [2, 6, 7, 8, 9] by the required amount of annotated training data and input size of the architectures. In the application context of a phenotyping system, this is a limiting factor because plants of various sizes, species and phenotypes are studied, yielding a timely and cost intensive setup for the segmentation of each variation infeasible. Therefore, well generalising methods are needed for feasible plant segmentation. This thesis approaches the plant scan segmentation problem by proposing a morphology-based method to semantically segment plants into stem and leaf area and a method for segmenting single leaf instances from the predicted leaf area of the first method, based on the Watershed algorithm [1].
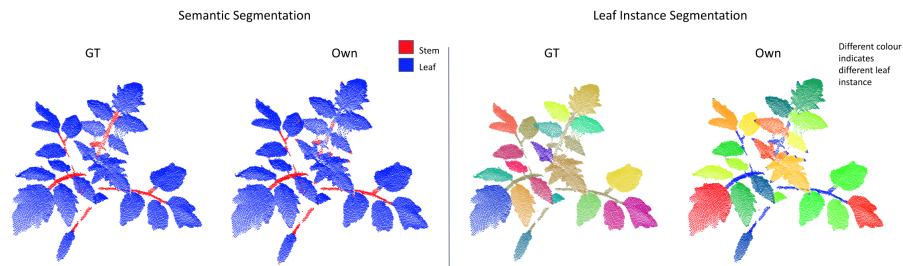

Figure 1: Segmentation predictions of the proposed methods (Own) on a tomato plant scan, next to ground truth labeling (GT).

Methods: For evaluating the proposed methods segmentation performance, two top-view plant scan data sets (Cucumber, Tomato) are created using the Phenospex Traitfinder system and annotated on a semantic and instance level. Top-view laser scanning only captures the upward facing surfaces of the plants and thus the scans can be described as the combination of planar surfaces representing the different plant parts.

The semantic segmentation of the plants into stem and leaf area is based on the observation that leaves are represented by wider planar surfaces, while stem parts are represented by more linear planar representations. The method uses this characteristic by replicating the mathematical-morphology operation of opening, used in image processing, on point cloud scans. The stem is identified by first detecting the surface edge points (using SBD from [5]), then dropping all points that are close to the boundaries and finally regrowing the dropped points that are close to the areas that are not dropped in the previous step. Through the removal, all thin linear stem structures are dropped while the centres of the wider leaf areas are retained. Following, the leaves are fully regrown while the stem areas remain removed. A segmentation prediction of this method is displayed in Figure 1 on the left.

The identification of single leaf instances from plant scans is difficult if two leaves are either touching in the scan or are connected via a stem part. Therefore, the problem of single leaf identification is approached by a leaf splitting method that uses the convex-ish shape of the leave representation in the scan for segmentation. Initially, each subpart of the point cloud belonging to the predicted class "leaf", that may contain connected leaves, is projected to 2D using the 3D distances of the points to the surface edge points as pixel values. Then the local distance maxima are determined to serve as seed points for the Watershed algorithm [1]. To filter wrong seed points (e.g. due to the leaves not being perfectly convex) a novel pre-flooding technique, altering the created distance map, is used to combine seed points belonging to the same leaf to prevent over-segmentation. Finally, the segmentation of the connected leaves is done using the Watershed algorithm and the outcome is projected back to the point cloud scan. A segmentation prediction of this method is displayed in Figure 1 on the right.

Table 1: Semantic segmentation results of Own and alternative methods.

Data Set	Metric	Own		Naive		FPFH-10		FPFH-100	
		Mean	Sd.	Mean	Sd.	Mean	Sd.	Mean	Sd.
Cucumber	mIoU	**67.03**	12.69	52.46	12.14	59.22	6.68	57.37	6.06
Tomato	mIoU	**80.31**	6.17	45.53	1.40				

Results and Discussion: The proposed methods (Own) were applied to both data sets to evaluate the segmentation predictions in comparison to the naive segmentation methods of the processing pipeline by Phenospex (Naive/CC). Further, the surface feature based method by [10] is evaluated on the cucumber data set for comparison (FPFH-10/FPFH-100). The semantic segmentation method was able to segment both studied plant species better than the alternatives (see Table 1), indicating that the method works successfully across different plant species (mIoU and mCov defined in [5]). However, the method tends to predict leaves as stem in areas where leaves grow vertical or highly optical-occlusion affected scan areas. Additionally, the leaf segmentation method displayed effective segmentation of connected leaves of various sizes and shapes on the two data sets (see Table 1). However, due to the dependency on the detected edge points, our proposed method has difficulties on vertical or highly occluded leaves.

Table 2: Leaf instance segmentation results of Own and alternative methods.

Data Set	Metric	Own		Own - Alt		CC		CC - SR	
		Mean	Sd.	Mean	Sd.	Mean	Sd.	Mean	Sd.
Cucumber	mCov	83.12	11.88	**88.48**	10.28	75.10	19.56	69.10	17.99
Tomato	mCov	**88.47**	5.59	87.69	3.50	35.48	7.48	35.21	5.85

Conclusions: Overall, the developed methods proved the applicability of morphological-inspired non-learning based methods for plant segmentation on top-view scans by exploiting the high structure of the data and plant growth paradigms shared by the two species. The segmentation using the developed methods might help in applications such as plant breeding for the development of drought-resistant crops or the automatic screening of plants in vertical farms. Additionally, the better segmentation of connected plant parts can enable tighter spacing of the plants during scanning and thus increase throughput of the scanning system.

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