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Development of a Camera System for Measurement of Geometry Parameters of Individual Wheat Plants

Semester Project

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2020

Abstract

Knowledge on geometry parameters is important in radiative transfer modeling, functional-structural plant modeling, and breeding of plants.

In this project I built a camera system (the Plant Geometry Sensor) that extracts plant geometry from images of wheat plants and derives parameters of interest from the extracted geometry.

In a field experiment I evaluated the repeatability of these measurements by means of heritability estimates to check their applicability to be used as selection criteria in the context of plant breeding.

The experiment showed that the Plant Geometry Sensor is an efficient method for measuring several geometry parameters with a good trade-off between accuracy, complexity and cost.

Keywords: plant architecture, plant morphology, image analysis, plant model.

Contents

Chapter 1

Motivation

1.1 High Throughput Phenotyping

Phenotyping is the quantification of plant traits, e.g., height, reflectivity, growth speed, and yield. In this project I am only looking at geometric traits, like plant height, leaf length, and leaf angle. While today genomic information is easily available and affordable, phenotyping often comes with high manual labor costs. High throughput phenotyping is an effort to reduce the amount of labor needed by utilizing automation of data capture and/or data processing[1] through methods such as automated image processing.

1.2 Importance of Plant Architecture

Knowledge on geometry parameters is important in radiative transfer modeling, functional-structural plant modeling, and breeding of plants.

Yield is a complex trait that is the result of many processes controlled by secondary traits or environmental influence. This makes breeding for increase in yield by direct selection inefficient as one can not distinguish between environmental and genetic influence. Instead one should try to understand the influences of secondary traits on yield and select based on these secondary traits [2]. This is the goal of functional-structural plant modeling.

Functional-structural plant models model the architecture and physiological processes of plants [3]. To calibrate or verify these models real-world measurements of plant architecture are needed.

Once the influence of a secondary trait is understood and an optimal value for a given environment has been found breeders can select plants using this secondary trait. Of course for that they again have to be able to measure the trait.

Another application where plant geometry is of interest is radiative transfer modeling. These models allow simulating remote sensing images by describing how light is reflected by crops. Models that treat leaves as turbid media such as DART [4] require the distribution of leaf normals. Other ray tracing based models such as described in [5] require a 3D mesh model of the plant.

The goal of this project is to build a camera system that extracts the plant geometry (wireframe model of the plant) from images and to derive parameters of interest from the extracted geometry. This system will be called the Plant Geometry Sensor (PGS). As part of this system I developed a mobile measurement station that holds plants between the camera and a black background, and image processing software for extracting the plant geometry from images taken in this measurement station.

In the context of functional-structural plant modeling and plant breeding the derived parameters should be strongly related to the genome to be useful for improving yield [2]. For this reason I will analyse the heritabilities of the extracted parameters.

Chapter 2

Developed Methodology

2.1 Measurement Setup

2.1.1 Measurement station

I decided to build a mobile measuring station (Figure 2.1) that holds individual plants, which were cut right above the soil level. Direct measurements in the field would have been more complex as the wheat plants in the field strongly overlap and separating them in images is probably not feasible even with depth information available (Figure A.1).

The measurement station holds the stereo camera in front of a black background, the plant can be put into a clip and pictures taken. The background is 1.3m high and 0.6m wide, thus plants of up to 1.3m height can fit into the measurement station. The plant clip is located at a distance of 22cm from the background.

The camera is mounted horizontally, because in the vertical orientation the depth information of the stem is often incomplete (aperture problem), even though mounting it vertically would utilize the resolution better. Because of this the camera has to be placed at a distance of 1.3m from the background to fit the whole plant into the image.

By removing a few screws the measurement station can be folded together for easier transportation, compact storage, and protection against scratches during storage (Figure 2.2).

2.1.2 RealSense™ Stereo Camera

For taking images of the plants I chose the Intel® RealSense™ D435i as its depth perception allows measuring absolute dimensions without calibration. All its sensors are integrated into a robust housing which makes this camera well suited for mobile, outdoor use in contrast to custom built stereo imaging systems built from individual cameras, which require recalibration after every intentional or unintentional adjustment.

The RealSense™ consists of a stereo pair of infrared cameras, an infrared projector, an IMU and an RGB camera (Figure 2.3). In this project only the infrared cameras were used as they have a big field of view (Table 2.1) and provide a good contrast between plants and black background.

The camera has an integrated processor calculating depth information from the two infrared images. The infrared projector is supposed to aid the depth estimation by introducing structure in flat, evenly colored areas. However it did not prove to be useful when taking images of thin structures like wheat plants, so I disabled it.

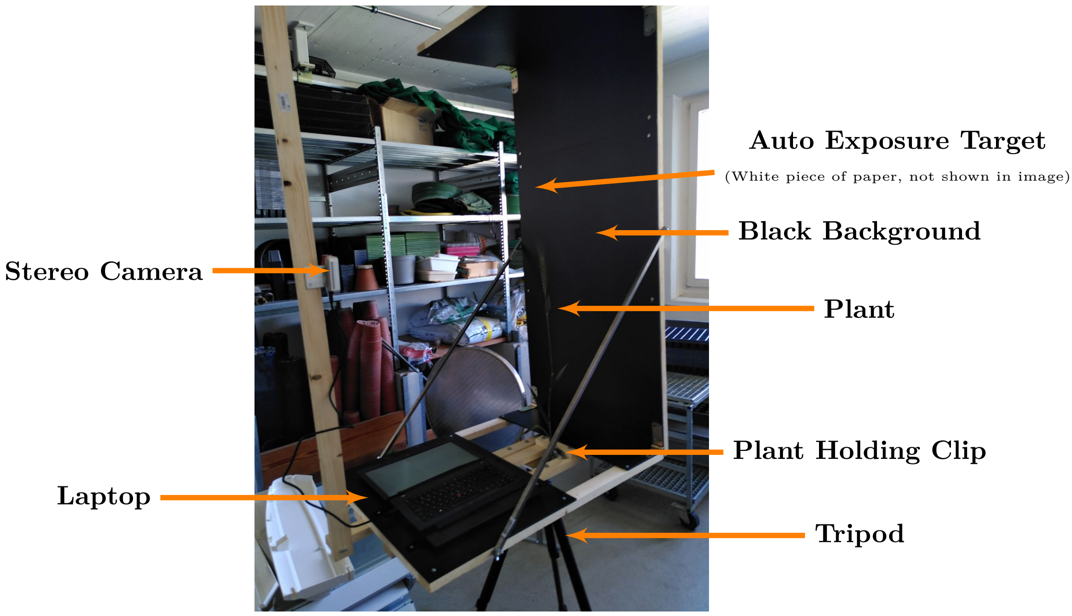


Figure 2.1: The measurement station

Figure 2.2: Folded measurement station

Figure 2.3: The RealSense™ D435i depth camera, with the left IR camera, IR pattern projector, right IR camera, RGB camera

Depth Field of View	H:87°/ V:58°/ D:95°
Depth Resolution	1280x720
IR Resolution	1280x720
RGB Field of View	H:69°/ V:42°/ D:77°
RGB Resolution	1920x1080

Table 2.1: Technical data of the RealSense™ D435i depth camera [6]

2.2 Software

The software I developed in this project consists of two parts: First, a capture application that connects to the RealSense camera and provides a user interface to take images and shows a preview of the plant model. Second, an analysis application that takes a set of stored images, extracts the plant geometry from those images, and derives geometry parameters from the plants' wireframe model. Figure 2.4 shows the flow of data in and between the applications.

2.2.1 Image capture

The image capture application displays the live image from the camera and provides a user interface to enter plot numbers and to show a preview of the plant geometry. The user can press a key to save the images to a folder named using the experiment name, the plot number, and the current time.

The capture application stores the images as they come from the camera, not the extracted plants. This allows making changes to the plant extraction after the images have already been taken.

The only setting that is determined during capture and cannot be changed later is the exposure of the camera. The exposure is continuously adjusted during capture using a white piece of paper fixed at a known location on the background as a reference.

2.2.2 Plant geometry extraction

The plant extraction is contained in the image capture application to show a preview of the plant geometry and also as a separate application to run the analysis on a large number of images that were already taken.

The structure of the plant is extracted from the 2D image instead of the 3D point cloud because the point cloud often has incomplete areas. It is easier to fill in these gaps in the depth information when the plant structure is already known. The missing depth data can then be interpolated along the skeleton of the plant.

These are the steps the plant geometry extraction application performs for a single set of images:

- **Local threshold (Figure 2.5b)**

  A local threshold on the infrared image separates the plant from the background using the OpenCV operation `adaptiveThreshold` with the `ADAPTIVE_THRESH_MEAN_C` method. A pixel is classified as foreground if its value is at least 100 higher than the mean of the pixels in the 5 x 5 pixel neighbourhood.

- **Skeletonization (Figure 2.5c)**

  Skeletonization is performed using the Zhang-Suen thinning algorithm [7]. From the skeletonized image the largest connected component is selected.

- **Build graph structure**

  From the resulting binary image an undirected connectivity graph is built. For each white pixel a node containing the coordinates of the pixel is created. Two nodes are connected if they are neighbors in the image.

- **Simplify graph structure (Figure 2.5d)**

  The resulting graph is simplified in two steps (Figure 2.6): First, small cycles (up to 10 edges) are collapsed into a single node. Such cycles sometimes occur at branches in the skeletonized image. Second, consecutive nodes without any branches inbetween are collapsed. The coordinate information of the removed nodes is stored on the edges for later use when building the wireframe model. After this operation nodes are only at leaf or stem ends or at branches, not at every pixel on the stem or leaf.

- **Find stem (Figure 2.5e)**

  The stem is found by looking for the shortest path between the highest node in the graph (most likely the ear of the plant) and the node closest to the position of the plant holding clip in the image.

- **Resolve overlapping leaves**

  Sometimes different leaves of the plant overlap in the image. In the simplified connectivity graph this will show up as a node with 4 or more edges. I try to resolve these overlaps and connect the edges of the corresponding leaf parts, removing the node at the intersection (Figure 2.7). Which edges should be connected is judged based on the angle between each two edges.

  To achieve this the line graph corresponding to the connectivity graph is built. The line graph is the graph containing a node for every edge in the original graph. Two nodes in the line graph are connected by an edge if the two corresponding edges in the original graph share a node. The weight of this edge of the line graph is a score based on the angle between the two edges in the original graph at the shared node (flatter angle is better).

  In the line graph the minimum spanning tree is found. The spanning tree is used to split nodes in the original graph:

  For each node in the original graph the edges of the node are grouped using a union-find data structure. Two edges are in the same group if their corresponding nodes in the spanning tree of the line graph are connected by an edge. If there are more than two groups of edges the node is split and all edges in the same group are connected to the same node.

- **Include depth information**

  The depth information is used to convert the pixel coordinates stored in the graph to 3d metric cartesian coordinates. The depth is filtered to reduce noise by setting each nodes depth as a weighted average of the depths of neighboring nodes 2.8.

- **Build wireframe model (Figure 2.5f)**

  The wireframe model resulting from this step consists of the stem as an ordered list of 3d points and the leaves as a list of ordered lists of 3d points. In this step some leaves are filtered out according to the following criteria:

  - **Distance of leaf from tip of plant**

    If the distance between the base of the leaf and the tip of the ear of the plant is smaller than 10cm the leaf is removed. These leaves are probably not actually leaves, but awns that were detected as leaves.

  - **Length of the leaf**

    If the leaf is less than 10 pixels long it it removed as it is probably not a leaf but some bump on the stem detected as a leaf.

- **Parameter extraction**

  The following geometric parameters are calculated from the wireframe model:

  - **Absolute leaf angle**

    The absolute leaf angle is the angle between the vector from leaf base to the tip of the leaf and the up axis of the measuring station.

  - **Leaf angle relative to stem**

    The relative leaf angle is the angle between the vector from leaf base to the tip of the leaf and the vector from stem base to the ear of the plant.

  - **Curvature depth**

    The curvature depth is the maximum distance between any point on the leaf and the line connecting the endpoints of the leaf.

  - **Leaf length**

    To calculate the leaf length the wireframe model of the leaf is approximated by linear segments of 10 pixels length to avoid overestimating the leaf length due to pixel staircase effects.

  - **Leaf distance**

    The leaf distance is the distance along the stem of the leaf's base to the base of the leaf above it. In case of the flag leaf it is the distance to the tip of the ear.

  - **Stem length**

    The length of the stem is calculated in the same way as the leaf length along the whole detected stem, including the ear of the plant.

2.2.3 Implementation and Performance

The software is written in C++. The image processing is done using the OpenCV library [8] and the graph structure is built using the LEMON library [9]. librealsense is used to interface with the camera and to convert image to cartesian coordinates.

Even without any manual optimization the image processing is quite fast. The analysis of a single plant takes 132ms on average on a laptop with an Intel(R) Core(TM) i7-7820HQ CPU. 62ms of this time is spent reading the files from the SSD.

The performance could easily be improved by implementing multi-threading, which could utilize the CPU better by already reading the next files from disk while the previous files are being processed and also make use of the multiple cores available on the CPU.

Some of the algorithms used also have potential for manual optimization.

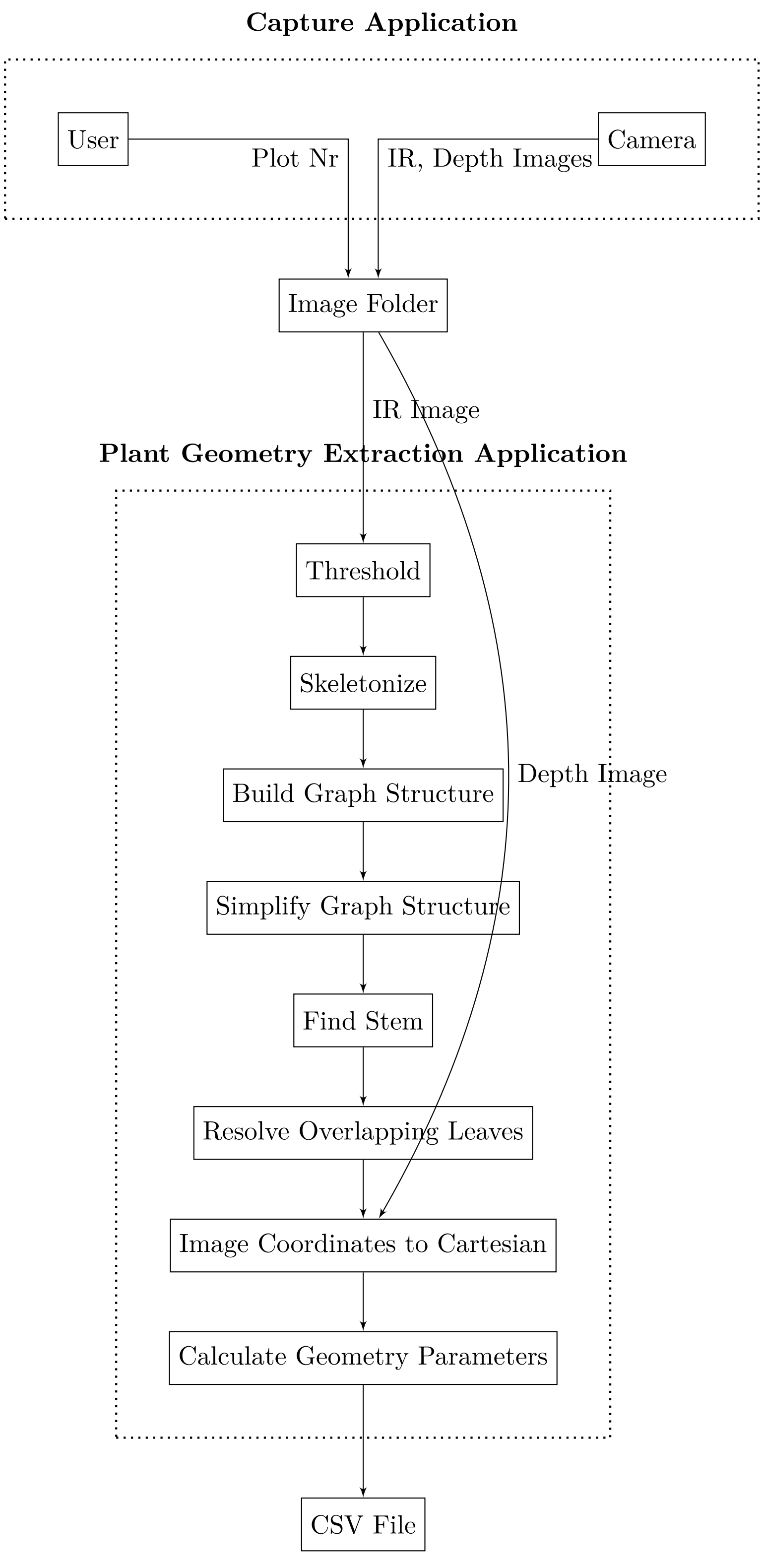
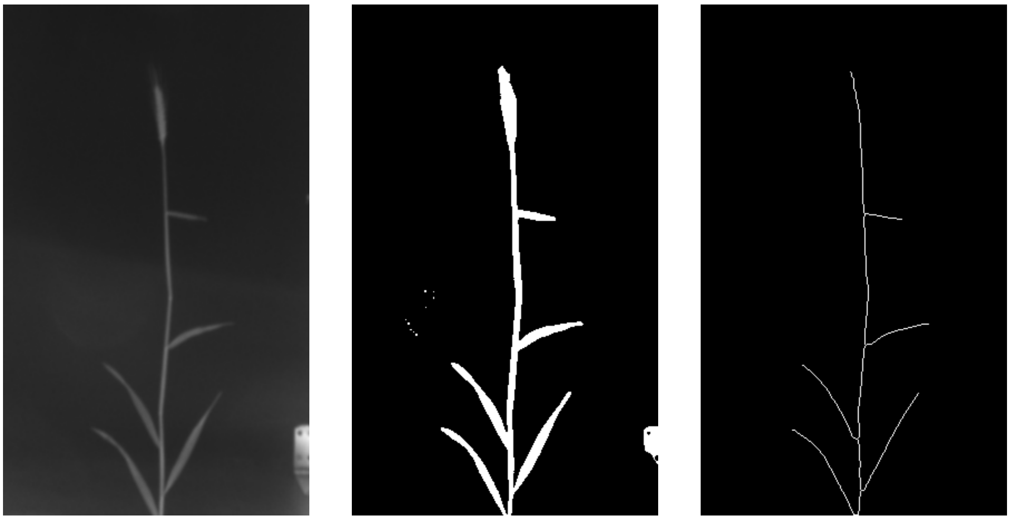


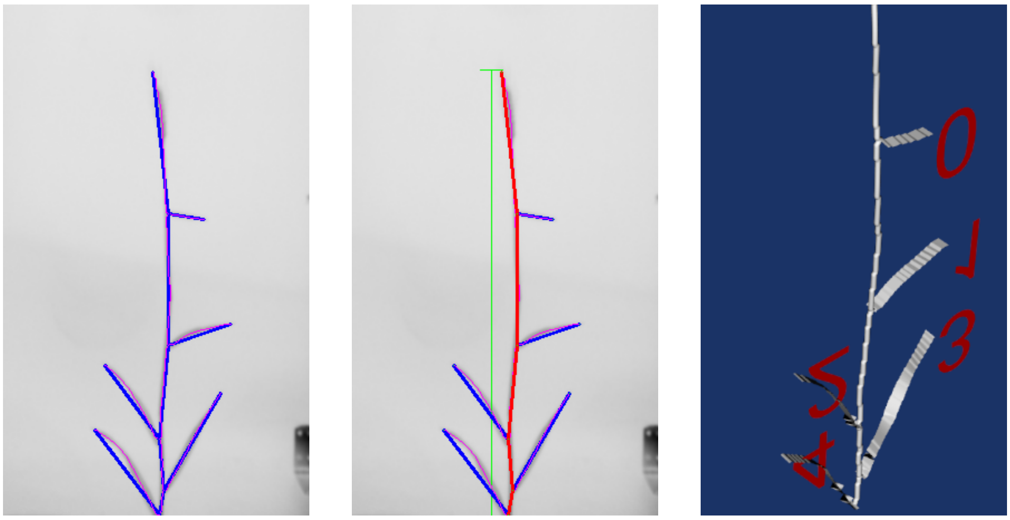
Figure 2.4: Dataflow in the software during capture and analysis



(a) Original infrared image

(b) Local threshold

(c) Skeletonization



(d) Simplified (thick) and original (thin) graph structure

(e) Detected plant with the stem marked in red

(f) Wireframe model with depth information. Numbers denote the leaf number starting at the flag leaf.

Figure 2.5: The steps of the plant geometry extraction

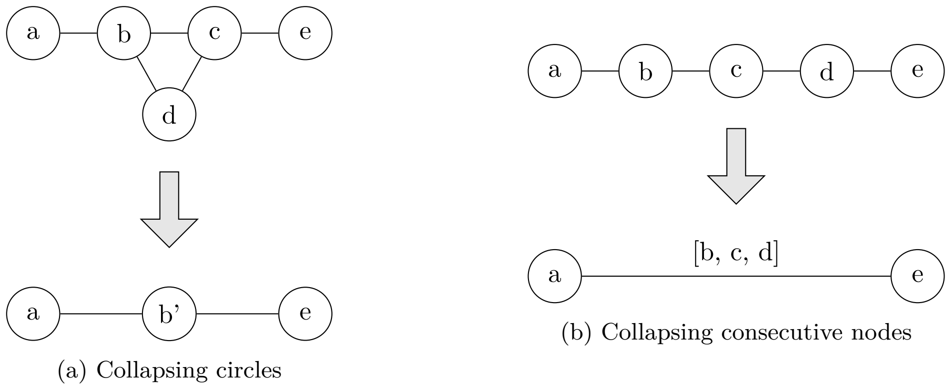


Figure 2.6: Simplification operations on the connectivity graph

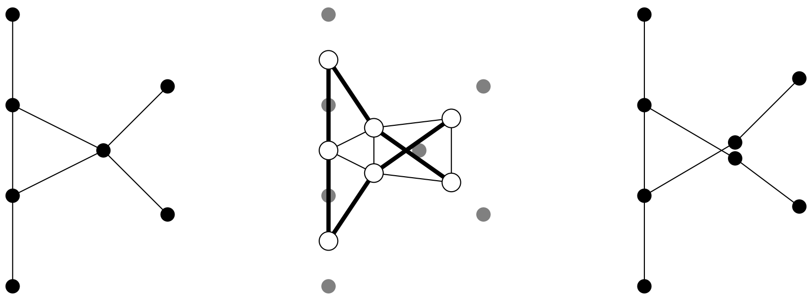


Figure 2.7: Untangling of overlapping leaves: On the left is the original graph. In the middle is the corresponding line graph. The nodes of the original graph are drawn in gray underneath for better visualization. The edges of the line graph that are part of the minimum spanning tree are drawn bold. On the right is the untangled graph using the information from the minimum spanning tree.

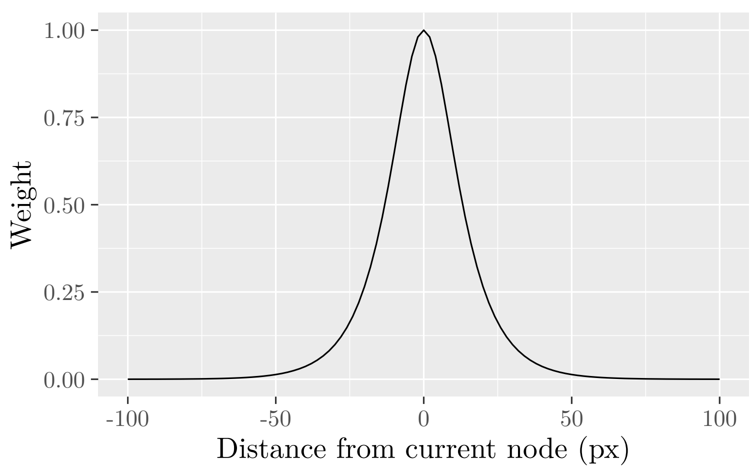


Figure 2.8: Smoothing kernel that is convolved with the depth values along stem and leaves

Chapter 3

Case Study

3.1 Experiment Setup

3.1.1 Laboratory Experiements

3.1.1.1 Repeatability of measurements under rotation

To check the accuracy of the depth measurements I took leaf length measurements of the same plant at different rotations. I would expect that the measurements are accurate if the leaves are approximately orthogonal to the camera's view direction and get less accurate the more the angle deviates from this orientation (Figure 3.1).

If a leaf is exactly parallel to the camera view direction it is not detected by the system. This is an inherent issue with the system as the plant is only photographed from a single angle. In practice this is not a problem though, as the plant can be oriented by the user in such a way that every leaf can be seen by the camera.

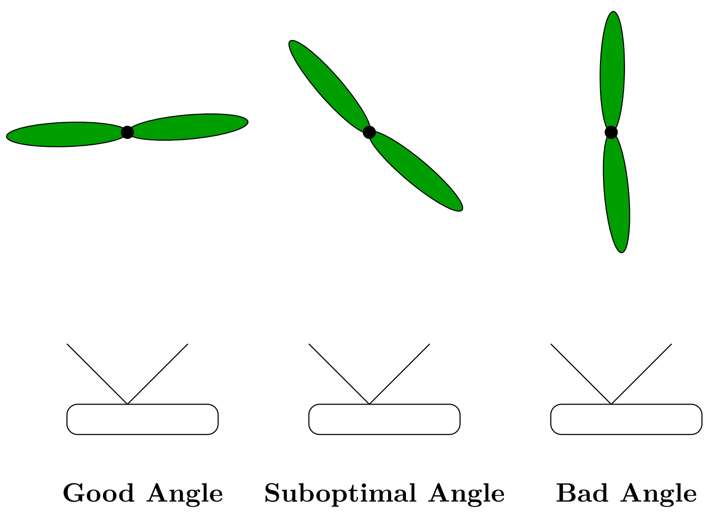


Figure 3.1: Examples of plant orientations that I expect to lead to good and bad results

3.1.2 Field Experiment

To test the practical usability and the quality of the measurements the system was experimentally evaluated at the Field Phenotyping Platform (FIP) [10] at the Eschikon Field Station of ETH Zürich.

3.1.2.1 Fields

Figure 3.2: The plots of the ETH FIP phenotyping site. We measured the marked plots in lot 6 with 3 replications and a subset of 8 genotypes from lot 1 with 2 replications.

The FIP field contains six lots on two of which many different varieties of winter wheat in small plots (1x1.7m on Lot 1, 1x4.7m on Lot 6) are grown (Figure 3.2, 3.3). Lot 6 contains winter wheat varieties from the Swiss list of recommended varieties, as well as new varieties to be compared against existing ones. Lot 1 contains a diverse selection of European varieties with different heights.

Figure 3.3: Plots of winter wheat on lot 6

3.1.2.2 Measurement procedure

Measurements were done on the 02. and 03.06.2020 after the heading stage but before senescence. One person cut the main stem of three plants from every plot and another person put these into the measuring station and took the measurements. For the 108 plots that were measured on lot 6 this took 3.3 hours, resulting in a measurement time of 37 seconds per plant.

Additionally, for replication 1 and 2, a third person took pictures of the flag leaves of the same plants in front of reference sheets. From these pictures the length of the leaves can be automatically extracted. These length measurements will later be compared to the length measurements from the measuring station.

3.1.2.3 Accuracy of length measurements compared with Grid pictures

To test the accuracy of leaf length measurements reference values were measured using a method already in use at the crop science group: The flag leaves are cut from the plants, put on paper sheets with a reference grid (Figure 3.4), and photographed using a DSLR camera. Using a MATLAB script these images are rectified, segmented, and the leaf lengths extracted.

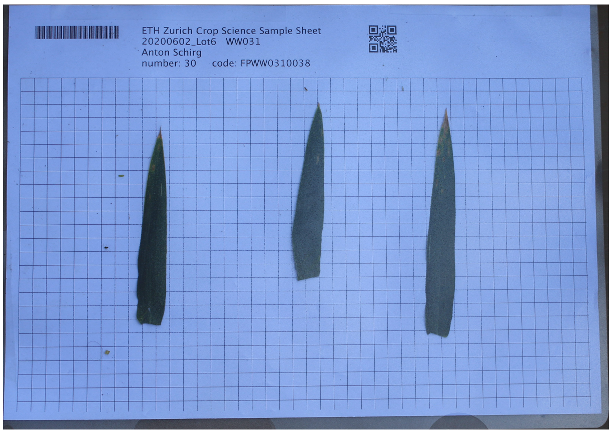


Figure 3.4: Flag leaves photographed on a sample sheet with reference grid

3.1.2.4 Heritability

To evaluate whether a parameter could be used in breeding and whether it can be measured in a reproducible way I calculated the heritabilities of all parameters measured by the PGS.

The heritability H_2 is the ratio of genotypic variance σ_g^2 to phenotypic variance σ_P^2 [11, p. 126]:

$$H_2 = \frac{\sigma_g^2}{\sigma_P^2} \tag{3.1}$$

A parameter having a low heritability can have multiple reasons: The trait might not be dependent on the genotype but is instead determined by environmental influence. Or the measurement method does not measure the trait in a reproducible way, i.e., introduces a lot of noise into the phenotypic values. In either case the measured parameter is not useful in breeding.

To estimate the heritability, for each geometry parameter a linear mixed model is fitted to the data according to the following formula:

$$p_{in} = \mu + g_i + r_n + \epsilon \tag{3.2}$$

where p_{in} is the measured parameter of genotype i in replication n, μ is the mean effect, g_i is the genotypic effect of genotype i, r_n is the replication effect of replication n, and ϵ is the residual error.

The heritability is then calculated as following analogous to [11, p. 150]:

$$H_2 = \frac{\sigma_g^2}{\sigma_g^2 + \frac{\sigma_\epsilon^2}{R}} \tag{3.3}$$

Here σ_ϵ^2 is the residual error variance, and R is the number of replications (3 for lot 6, 2 for lot 1).

3.1.2.5 Manual Flag Leaf Angle Rating

As a baseline comparison I did manual ratings of leaf angles according to [12, p. 111]. In each plot I recorded the flag leaf angle of three plants as either pointing up, sideways or down. This took 40 minutes for the entire lot with 108 plots, or 7.4 seconds per plant.

3.2 Results and Discussion

3.2.1 Laboratory Experiments

3.2.1.1 Repeatability of measurements under rotation

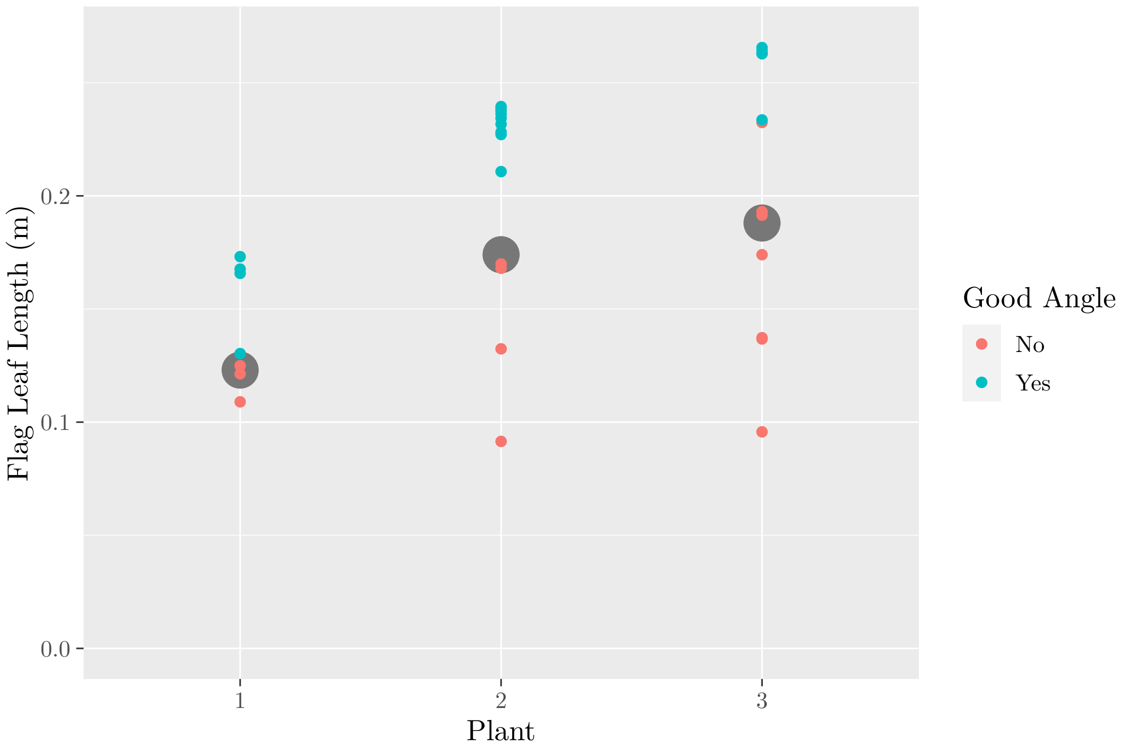


Figure 3.5: Measured leaf lengths of 3 plants, put into the measurement station at different angles. The big gray dots are manual measurements using a ruler. Light blue dots are measurements manually labeled as taken at a good angle.

Figure 3.5 shows the results of the rotation experiment. As long as the plants are put into the measuring station at good angles the repeatability of the measurements is good. The leaf lengths are however consistently overestimated. At suboptimal angles the leaf lengths can be underestimated by about 50%. This shows that the depth information from the RealSense™ camera is not accurate enough on thin structures at steep angles, or that the influence of the depth measurements is diminished by the depth smoothing.

The depth smoothing might be introducing a bias towards estimating the leaves to be orthogonal to the viewing direction. A smoothing spline might be a better alternative to the convolution with a smoothing kernel as it would not tend to move the depth values at the leaf ends towards the values at the center.

3.2.2 Field Experiment

3.2.2.1 Accuracy of length measurements compared with grid pictures

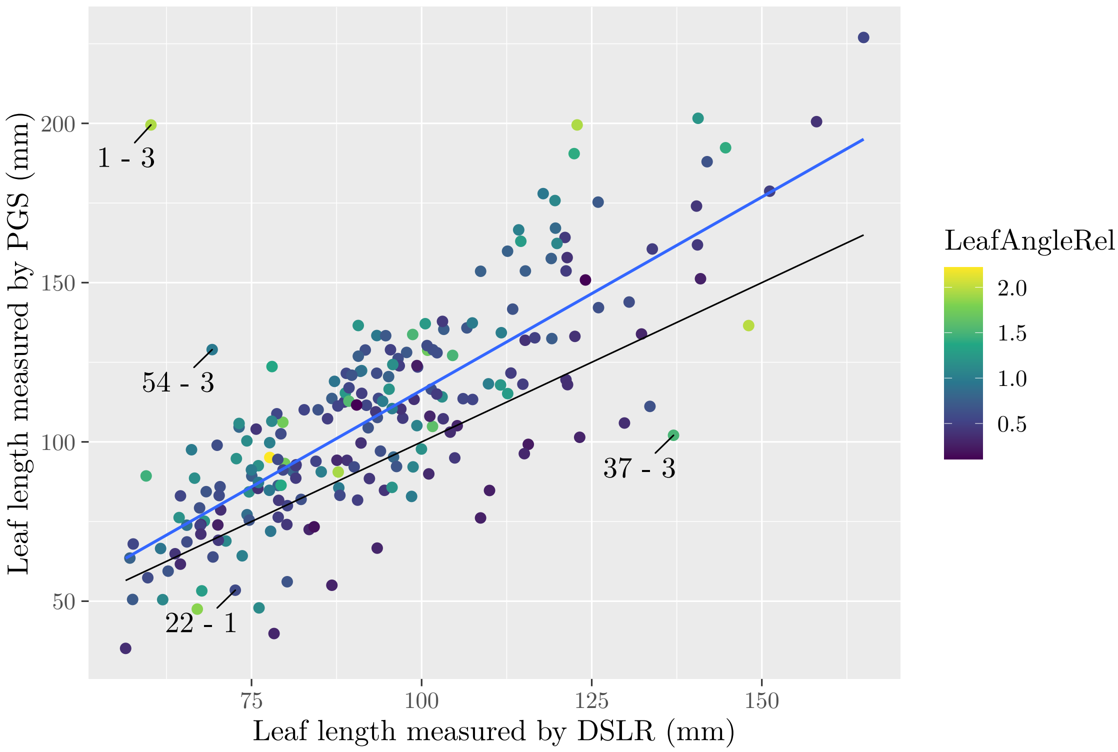


Figure 3.6: Leaf length measurements of the PGS compared with leaf lengths extracted from images of leafs taken in front of a clean background with a DSLR. The blue line is a linear fit through the data, the black line is the ideal case where both systems measure the same values.

Figure 3.6 shows the correlation between the leaf lengths measured by the PGS and the reference measurements described in section 3.1.2.3. The PGS tends to overestimate the leaf length by about 10%. This could be due to pixel staircase effects which lead to an overestimation of the length of a path in the image. I tried to limit the influence of this effect by approximating the leaf shape using linear segments of 10px length. Another reason could be noise in the depth measurements. For this reason I implemented the depth smoothing, which however might even be to strong as seen in figure 3.9 and section 3.2.1.1.

There seems to be a tendency for the length of steeper leaves to be underestimated. This might be due to steep leaves overlapping with the stem in the image as seen in figure 3.7.

With a coefficient of determination of $r^2 = 0.59$ the correlation between the measurements of the PGS and the reference measurements taken as described in 3.1.2.3 is lower than I would have expected. However when comparing the heritability of the leaf lengths measured using the PGS with the reference method one can see that the heritability is only slightly reduced by the measurement error ($H_2 = 0.49$ for the PGS, $H_2 = 0.54$ for the reference method).

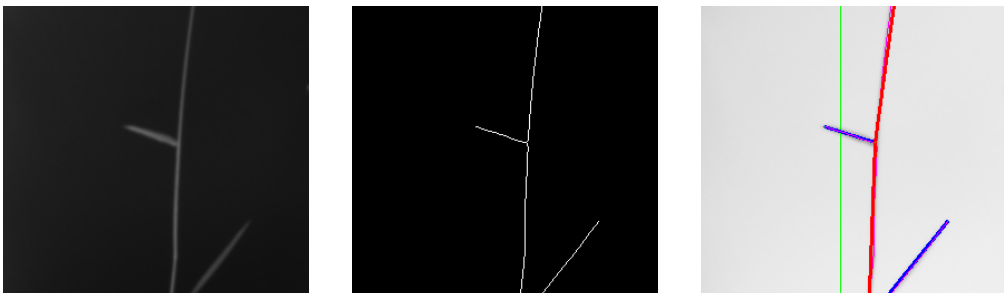
I selected some of the measurements with a high error and tried to find the reasons for the errors (Figures 3.7, 3.8, 3.9). The large error of plant 1-3 is most likely due to a manual error in plant ordering when taking measurements.

(a) Original infrared image (b) Local threshold (c) Skeletonization

Figure 3.7: Plant 22-1. The flag leaf length is underestimated because the leaf angle is steep and the leaf is overlapping with the stem in the image, so the skeletonization estimates the leaf base to be higher than it actually is

(a) Original infrared image (b) Local threshold (c) Skeletonization

Figure 3.8: Plant 54-3. The flag leaf is so steep that the software can not separate it from the stem. The leaf below is thus classified as the flag leaf, leading to a much higher value for the flag leaf length.



(a) Original infrared image (b) Skeletonization (c) Detected plant

Figure 3.9: Plant 37-3. The flag leaf was well detected in the 2D image, so probably the issue is with the depth data. The leaf might be pointing towards or away from the camera which was not detected by the stereo camera or smoothed too strongly by the depth smoothing leading to an underestimation of the leaf length.

3.2.2.2 Heritability of parameters

Table 3.1 shows the heritabilities of the parameters measured in 108 plots in lot 6 and 16 plots in lot 1 and the heritabilities calculated using the measurements from both lots combined.

Stem length is highly heritable. [13] reports an even higher heritability of 0.96. However the difference could be explained by a more diverse set of genotypes being analyzed in [13].

Leaf angles and leaf distances also have a pretty high heritability. For flag leaf angles the PGS shows a significant improvement over the baseline manual ratings done in lot 6. Here the heritability of both absolute and relative leaf angles measures using the PGS is 0.67 while the manual ratings have a heritability of 0.49.

The leaf length has a lower heritability, but as explained in 3.2.2.1 this seems to be mostly due to the lower genetic heritability of leaf length, not measurement noise.

Leaf curvature depth has a very low heritability. Possibly curvature depth can not be measured accurately enough as the leaf curvature seems to be generally quite small, or curvature is more dependent on environmental influences like temperature or moisture than on the genotype.

For most parameters measured in lot 1 the heritabilities are lower than in lot 6. However they are not directly comparable as the number of replications differs.

	Leaf level	Stem Length	Leaf Length	Leaf Angle Abs	Leaf Angle Rel	Leaf Curvature Depth	Leaf Distance
Lot 6	1		0.50	0.67	0.67	0.14	0.64
	2		0.34	0.61	0.63	0.31	0.75
	3		0.42	0.25	0.20	0.17	0.62
	NA	0.86					
Lot 1	1		0.39	0.33	0.39	0.07	0.73
	2		0.22	0.38	0.38	0.39	0.77
	3		0.26	0.55	0.55	0.01	0.66
	NA	0.86					
Lot 1+6	1		0.42	0.60	0.60	0.19	0.61
	2		0.30	0.41	0.41	0.27	0.69
	3		0.33	0.43	0.41	0.09	0.56
	NA	0.82					

Table 3.1: Heritability of parameters at different leaf levels (where applicable). Level 1 is the flag leaf. In lot 6, 3 replications of each genotype were measured, in lot 1, 2. The heritabilities for lot 1 and 6 combined were calculated using only replication 1 and 2 from lot 6, as the formula for heritability (3.3) only allows the same number of replications for each genotype.

Chapter 4

Overall Discussion of the Measurement System

4.1 Choice of the RealSense™ camera

The RealSense™ camera proved to be easy to set up, robust and inexpensive (~230CHF). Disadvantages were slightly blurry images (Figure 2.5a), suboptimal utilisation of the resolution due to the horizontal orientation of the camera (section 2.1.1), and possibly not very accurate depth information (Section 3.2.1.1).

Since I used a single camera the images were only taken from two very close positions. This made image processing relatively simple and efficient, however leaves in some orientations can not be detected. As an alternative a multi camera setup could be evaluated, e.g. using volume carving like described in [14]. This would make the setup more complex, expensive and less mobile though.

4.2 Software

The capturing software worked well in the field experiment. Taking and storing images was fast and automatic naming of the image folders using plot numbers and timestamps avoided mistakes in the assignment of measurements. The preview of the plant model helped to check during the measurements whether the images were acquired correctly, while storing the raw images was useful for later improvement of the model extraction.

The most complex part of the software is the resolving of overlapping leaves. While overlapping leaves were present in images taken in previous years using a different method this case never occurred in the field experiment, so possibly this could be removed from the software, reducing its complexity.

4.3 Measurement Station

The measurement station was quickly set up and ready for the experiment. The possibility of folding the station proved useful for storage and for transporting the measurement station onto the field. It was built using parts from a local hardware store with a total cost of 75 CHF (the plastic panes for the black background and the tripod were already available from earlier projects). Together with the cost of the camera this results in a total cost of the setup of 305 CHF (excluding the laptop).

4.4 Results of the field experiment

The heritability of leaf angle measurements using the PGS was significantly better than that of manual ratings (3.1.2.5).

The manual ratings were much faster though, and require no special equipment. The heritability of the manual ratings could potentially also be improved by using more than just three possible values. So when only a single geometry parameter should be measured, for example when selecting plants based on a known desired value for a parameter, manual rating might be the more efficient method.

When multiple geometry parameters or the whole wireframe model are of interest, for example when collecting data for functional-structural plant modelling, the PGS is an efficient measurement method with a good trade-off between accuracy, complexity and cost.

Chapter 5

Acknowledgments

I would like to thank Helge Aasen for his supervision of the project, his help with organizing and taking the measurements of the field experiment, his advice and feedback on the report and for helping me understand the surrounding context of the project. Norbert Kirchgessner also supervised the project. Furthermore he helped me build the measurement station and did the processing of the leaf size reference images. Thank you for that! I would also like to thank Radek Zenkl for helping me take the measurements using the PGS and Frederic Kislinger for taking the size reference images and helping me with additional PAR measurements. Thanks also to Marco Hutter for providing feedback based on the intermediate presentation. Additionally I want to thank the whole crop science group for the welcoming environment.

Chapter A

Appendix

Figure A.1: A single row of wheat plants photographed in front of a black background. The plants are close to each other and overlapping a lot which makes an automatic segmentation into single plants too difficult.

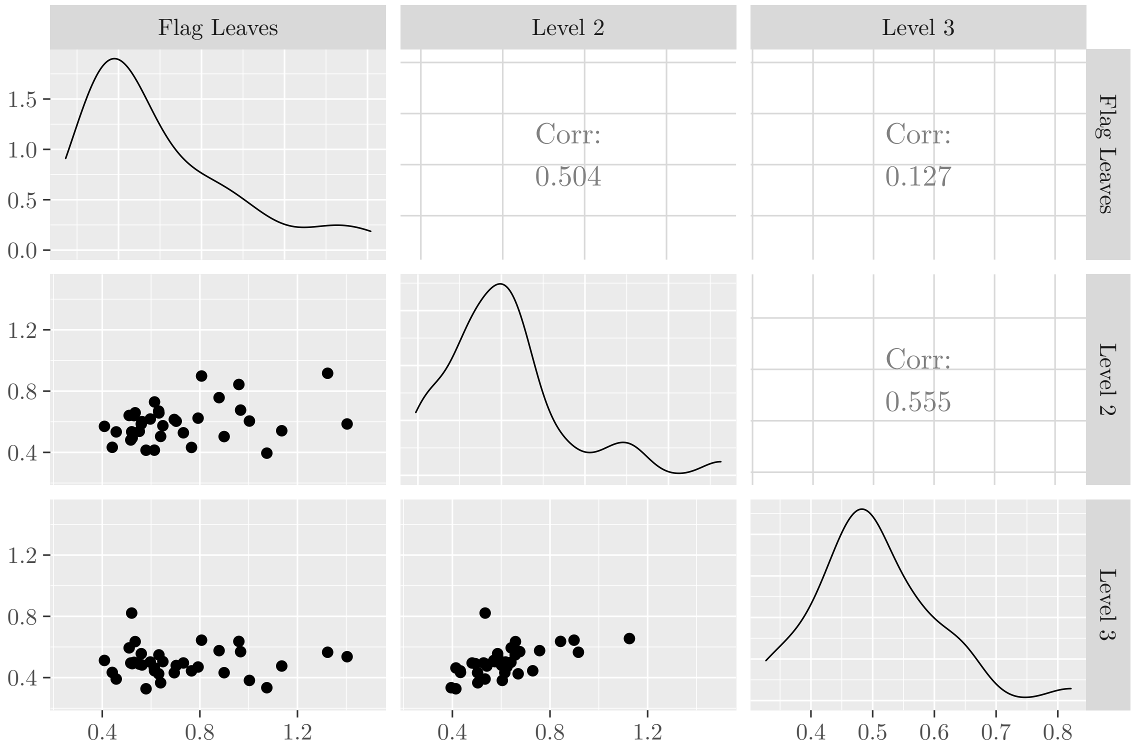


Figure A.2: Correlations between per genotype means of relative leaf angles at different levels. Interestingly, angles on adjacent leaf levels are well correlated while non-neighboring leaf levels are not.

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Title of work:

Development of a Camera System for Measurement of Geometry Parameters of Individual Wheat Plants

Thesis type and date:

Semester Project, 2020

Supervision:

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