High-resolution In-field Crop Scanning

Radu Alexandru Rosu, Sven Behnke
PhenoRob Core Project 1: In-field 4D Crop Reconstruction

- PIs: Sven Behnke, Maren Bennewitz, Lasse Klingbeil, Heiner Kuhlmann, Uwe Rascher, Cyrill Stachniss, Eduard Zell

- **Background:**
  - Plant phenotyping technologies have greatly increased in the past years and commercial services and infrastructures are becoming available
  - Methods to quantify relevant plant traits are still missing and correlation-based methods limit the universal interpretation

- **Objective:**
  Create time series of aligned high-resolution and geo-referenced 3D models of plants using optical and 3D data from a moving sensor platform. Extract novel phenotypic features of single plants and their evolvement over time for a better scientific understanding of the structural / functional dynamics of selected crops
Some features such as early signs of diseases or nutrient imbalance, can only be detected on the small scale. This requires a ‘close look’ on single organs and the option to follow the temporal development of single elements. Precise 3-D reconstructions of single plants in the field throughout the season.

The intelligent combination of different sensors that are brought in the right viewing geometry allows the quantitative, georeferenced mapping of fields. Combination of radiative transfer inversion and machine learning allows the extraction of novel traits. Fast method that can be used on larger fields across different sites.
Robots for Plant Phenotyping

- Various robots have been used for plant phenotyping
- Few of them have the capabilities for high-resolution scanning
In-Field 4D Crop Reconstruction

- Multiple 3D sensors + high-resolution cameras for in-field plant scanning
- 4D structural textured plant reconstruction
  - 3D + correspondences in time
  - Structural model of plant organs
  - Millimeter-scale geometry (e.g. mesh)
  - Sub-millimeter resolution RGB textures
  - Additional multi/hyperspectral textures
- For computation of phenotypic features
PhenoRob UGV

- Robot for in-field high-resolution plant scanning
- Interior of 1.5m x 1.5m
- Thorvald base
- 14 high-res RGB cameras
- 5 Photoneo laser scanners
PhenoRob Robots
UGV on PhenoRob Central Experiment Field
PhenoRob UGV Sensors

- 14× Nikon Z7 DSLR Camera
  - 45MP
  - 64–25600 ISO
  - 24-70mm Lens

- 5× Photoneo PhoXi® 3D Scanner
  - Computes mm-accurate 3D cloud and normals
  - Range 0.8m – 2.1m
PhenoRob UGV Sensors

- Block of 2× Nikon + Photoneo
  - Allows for stereo vision
  - Allows to combine and refine depth from RGB with depth from laser
PhenoRob UGV Sensors

- 2020 system with only 1 camera per block
PhenoRob UGV Sensors

- RGB images + fused point cloud from all laser sensors
More Cameras in 2021

- Added eight Nikon cameras
- Similar to a smaller-scale photogrammetry rig used in film industry to create digital twins of actors
Challenges for In-field Scanning: Lighting

- Dynamic light conditions
  - Cameras need to constantly adjust exposure automatically
Challenges for In-field Scanning: Plant Motion

- Moving plants in the wind
  - Needs fast shutter speed to avoid motion blur
Challenges for In-field Scanning: Non-rigid Vehicle

- Calibration between cameras changes due to non-rigid robot frame
  - Need on-line calibration
Camera Parameters

- All Nikon camera settings are programmable by the onboard PC
Camera Parameters: ISO

- All Nikon camera settings are programmable by the onboard PC
  - ISO: camera sensitivity to light
  - Too high = noisy images
Camera Parameters: Shutter

- All Nikon camera settings are programmable by the onboard PC
  - Shutter speed
  - Too high = dark photos
  - Too low = motion blur
Camera Parameters: Aperture

- All Nikon camera settings are programmable by the onboard PC
  - Aperture determines depth-of-field
  - Too high = blurred background
  - Too low = dark photos

- Set the aperture even lower => light diffraction effects
- Both dark AND blurry photos
Camera parameters

- Cameras need constant and automatic adjustment in the field.
- The best image is somewhere within the exposure triangle
In-field Camera Dynamic Exposure

- Start with reasonable camera settings (low aperture, high speed, and low ISO)
- Cameras periodically capture low-resolution images
- Histogram is computed
- ISO of cameras adjusted (within allowed range) to avoid clamping white or blacks
- If ISO is outside the allowed range → change shutter speed
- If still clamped → change aperture
Moving Plants

- Keep shutter speed low (<5ms)
- This creates darker photos.
- We added panel lights inside the robot.
Calibration between cameras

- Robot frame twists while driving
- We added fixed ArUco calibration patterns on the sides of the robot
- At least one side is visible from each camera
- Bundle adjustment to correct camera misalignment (Ceres)
Photoneo

- 3D sensors with millimeter accuracy.

- Nikon RGB

- Photoneo point cloud
Photoneo

- 3D sensors with millimeter accuracy
- Struggle in strong sunlight
- Emit red visible light while scanning
- Multiple Photoneos cannot scan the same volume simultaneously
- We trigger the Photoneo scanners sequentially
Photoneo + RGB

- Given good calibration between Photoneos and RGB one can recover also a textured mesh with a high resolution texture from the Nikon camera
Photoneo + RGB

- Fine detail of small plants can be captured
- Image shows aggregation from all Photoneos calibrated using the ArUco patterns and colored with RGB from Nikon
Stereo Depth

- Photoneo depth can be refined with the depth from the stereo pair of Nikons → Need computation of stereo disparity

- RGB

- PatchMatch with local expansion [Taniai 2017]
Stereo Depth

- CNN approaches surpass classic methods in stereo matching

RGB

Hierarchical Deep Stereo
[Yang et al. 2019]
Stereo Depth Limitations

- Hierarchical Deep Stereo (Yang et al.) require supervised training on datasets with ground-truth depth
- Can process only binocular stereo data and not multi-view stereo
Multi-view Stereo (MVS) Depth

- NeuralMVS: Bridging Multi-View Stereo and Novel View Synthesis (Rosu and Behnke 2021)
  - Unsupervised training → trained only with image reconstruction
  - Can process multiple images in order to refine the depth
MVS Depth Approach

- Depth reconstruction as novel view synthesis.
- In order to predict a novel view network is forced to predict correct depth.
- Differentiable sphere tracing to iteratively refine depth.

[Rosu and Behnke 2021]
MVS Depth Example Result

Results on Real Front-Facing dataset
Pheo4D Data Set

- Created with handheld lidar
- Annotated plant organs
- [Schunck et al. PLoS ONE 2021]
Phenotyping: Instance Segmentation


- 3D points are embedded in a permutohedral lattice where convolutions are defined
- Output of network is clustered into individual leaf instances
PhenoRob Central Experiment Scanning

- Scanned weekly
  - 16 sugarbeet plants with 4 levels of herbicide (0%, 30%, 60%, 100%)

- Sugarbeet 100% herbicide
- Sugarbeet 0% herbicide
PhenoRob Central Experiment Scanning

- Scanned weekly
  - 8 corn plants of 4 different varieties
    - Caramelo, Khan, Sugarnugget, Mirza

- Sugarnugget corn
PhenoRob Central Experiment Scanning

- Scanned once
  - 16 Lupin plants
  - 16 Brassica

- Brassica
- Lupin
Phenotyping with Near-canopy UAV

- DJI Mini 2 copter
- <250g => not dangerous
- 12 MP RAW camera on gimbal

Sugar beet
Phenotyping with Near-canopy UAV

Maize

Beans
Phenotyping with Near-canopy UAV
Phenotyping with Near-canopy UAV

Sugar beet
Phenotyping with Near-canopy UAV

Maize
Conclusions

- High-resolution in-field plant scanning is challenging
  - Lighting
  - Wind
  - Wether
  - Occlusions
- Developed UGV with many sensors
- Started regular plant scans on the field
- Developed initial reconstruction methods
- Much work is ahead …
Thank you for your attention!

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