High-resolution In-field Crop Scanning

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PhenoRob Core Project 1: In-field 4D Crop Reconstruction

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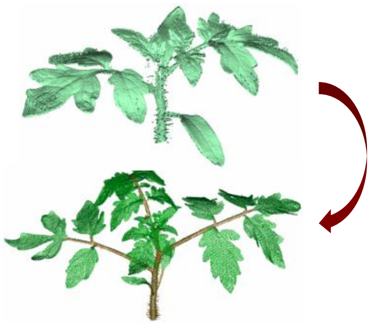
- **Background:**
  - Plant phenotyping technologies have greatly increased in the past years and commercial services and infrastructures are becoming available
  - Methods to quantify relevant plant traits are still missing and correlation-based methods limit the universal interpretation
- **Objective:**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

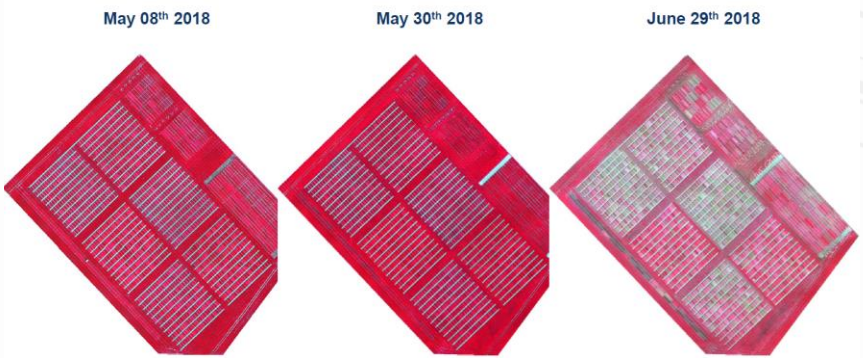
CP1: Two Scales – Complementary Throughput and Resolution

Detailed reconstruction of single plants & their organs



- 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

Larger scale mapping of structural & functional traits



- 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

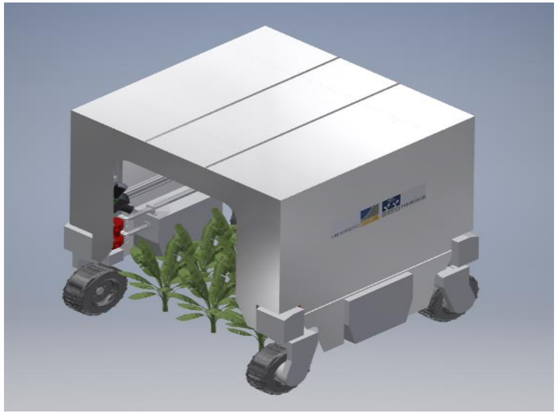
- 4D structural textured plant reconstruction
  - 3D + correspondences in time
  - Structural model of plant organs
  - Millimeter-scale geometry (e.g. mesh)
  - Sub-millimeter resolution RGB textures
  - Additional multi/hyperspectral textures
- For computation of phenotypic features

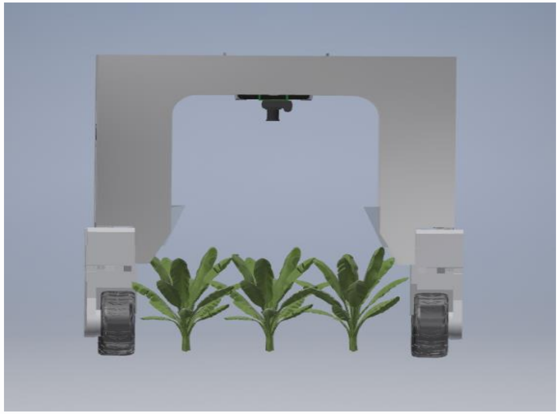
Potted plant reconstructed in 3D

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

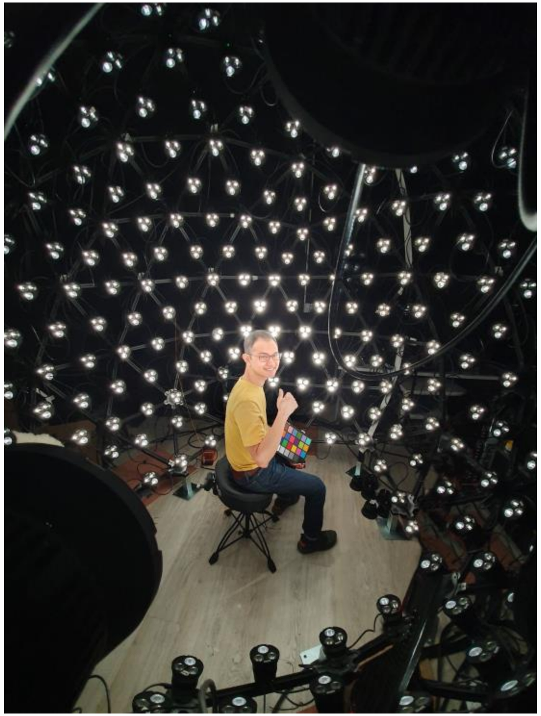
- 2020 system with only 1 camera per block

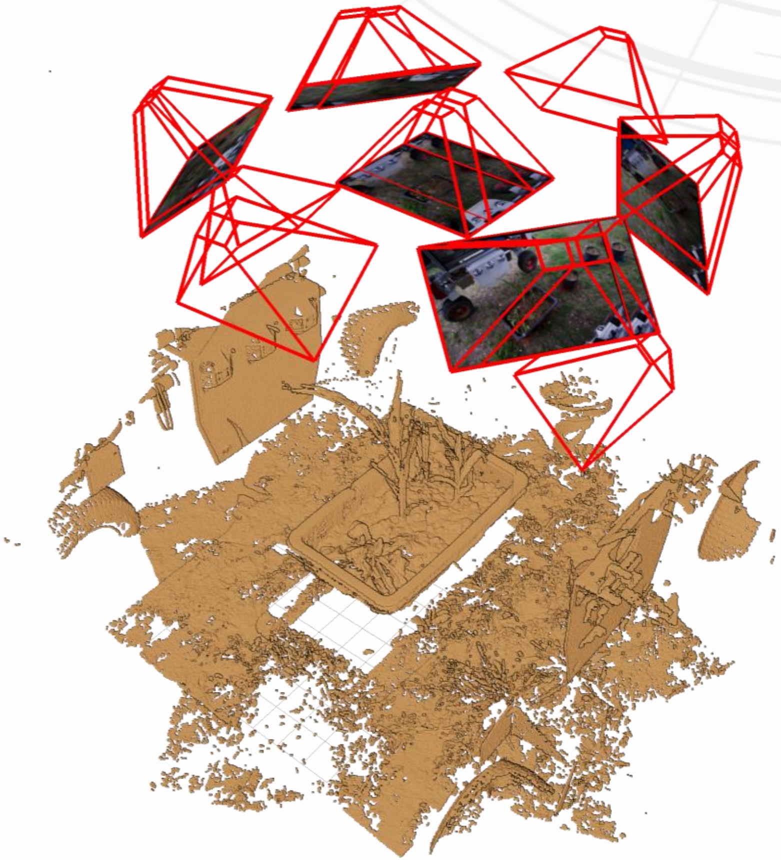
PhenoRob UGV Sensors

- RGB images + fused point cloud from all laser sensors

More Cameras in 2021

- Added eight Nikon cameras
- Similar to a smaller-scale photogrametry rig used in film industry to create digital twins of actors



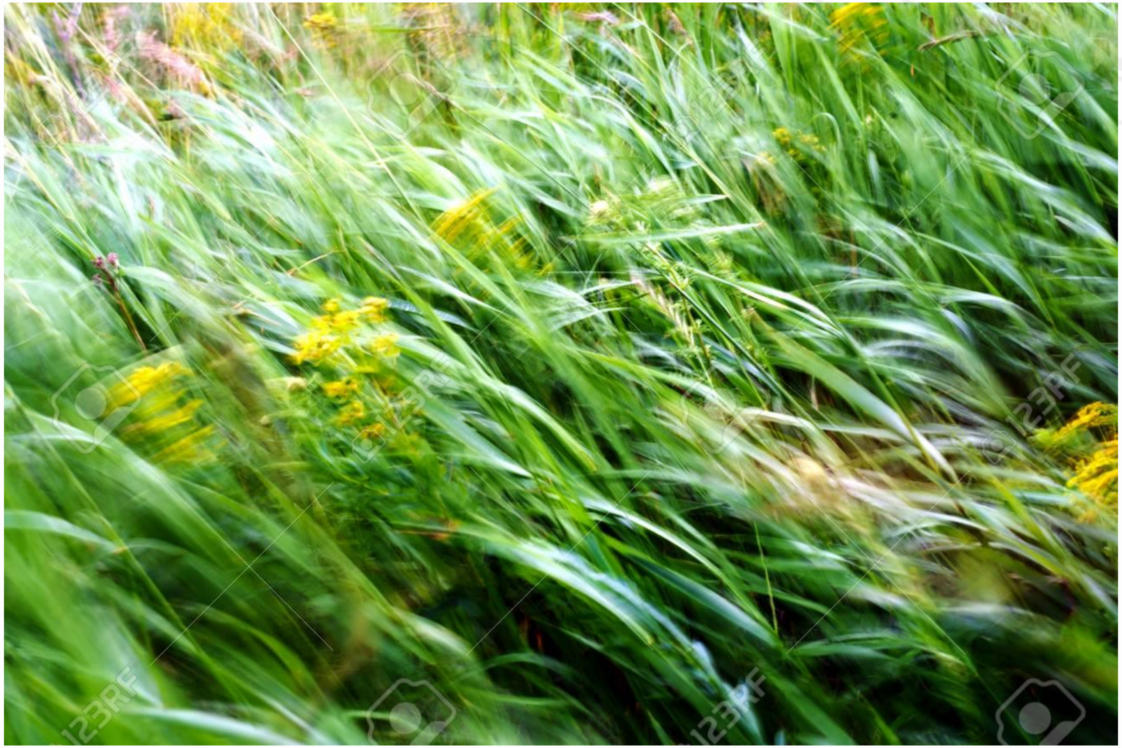


Challenges for In-field Scanning: Lighting

- 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

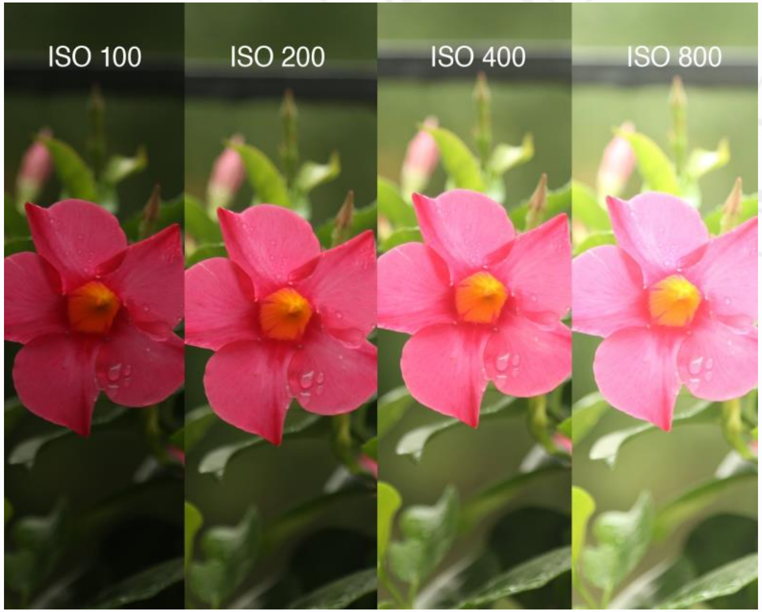
- Calibration between cameras changes due to non-rigid robot frame
  - Need on-line calibration

Camera Parameters

- All Nikon camera settings are programmable by the onboard PC

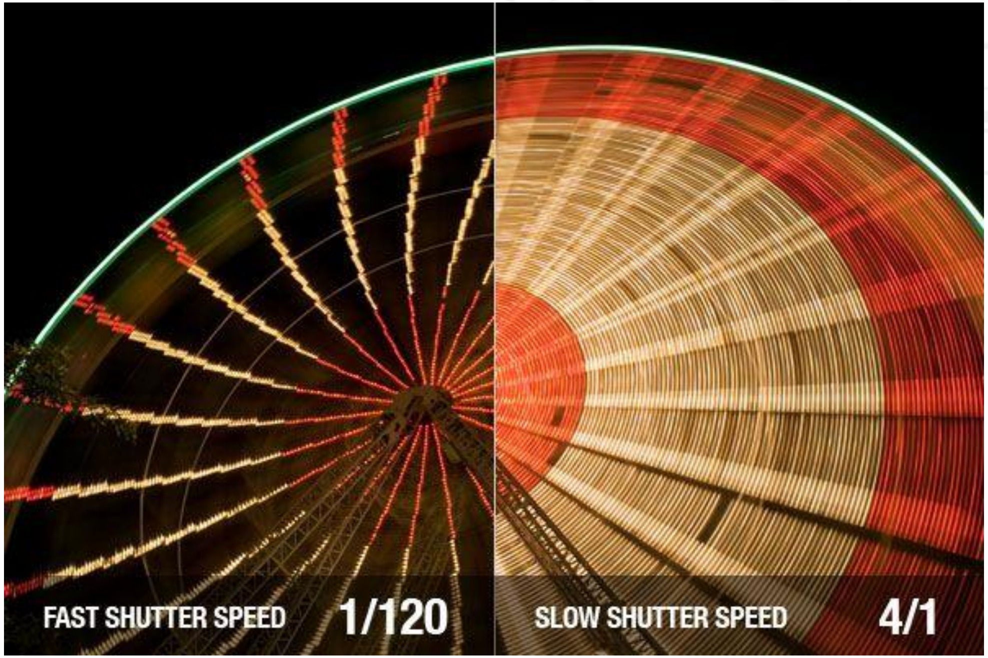
Camera Parameters: ISO

- 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



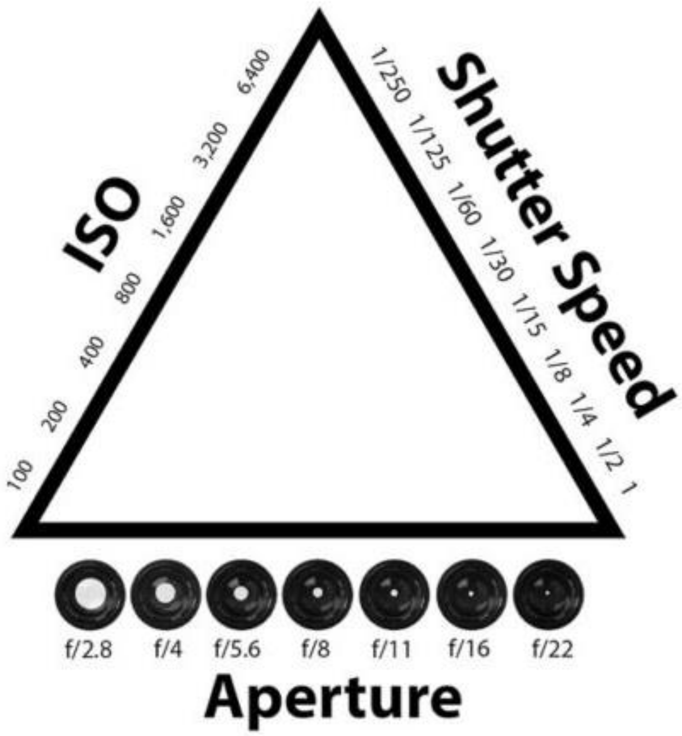
Camera Parameters: Aperture

- 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

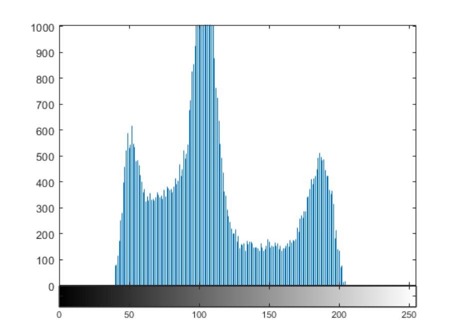
Camera parameters

- 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

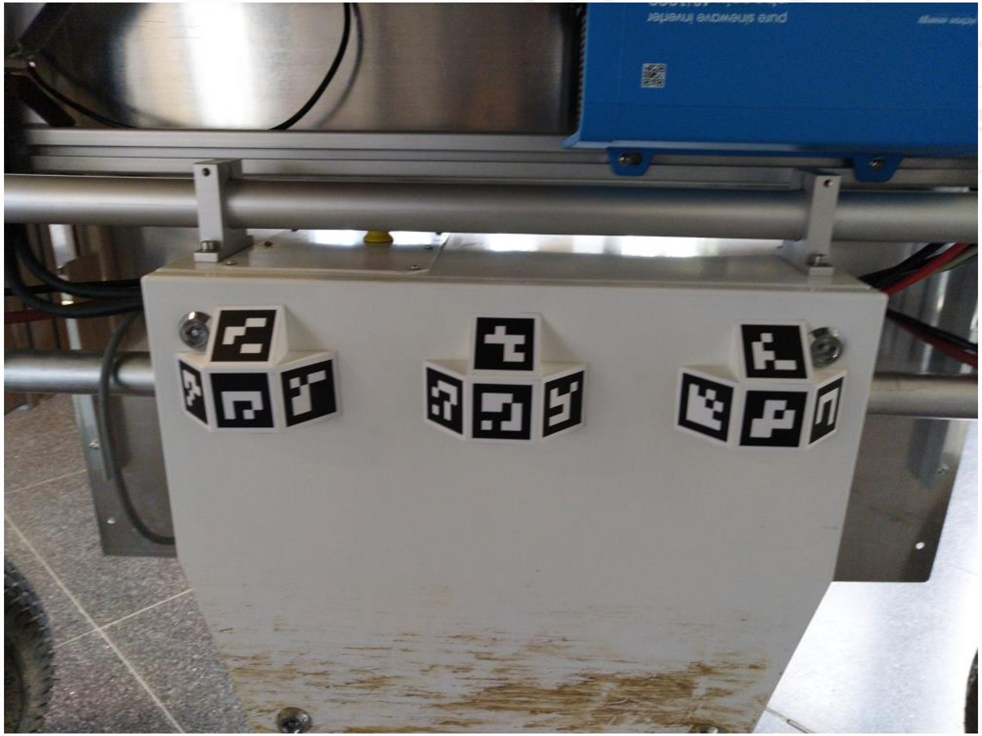


Moving Plants

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

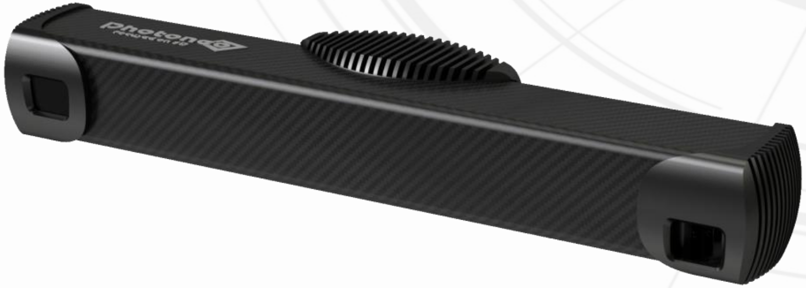
Calibration between cameras

- 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)

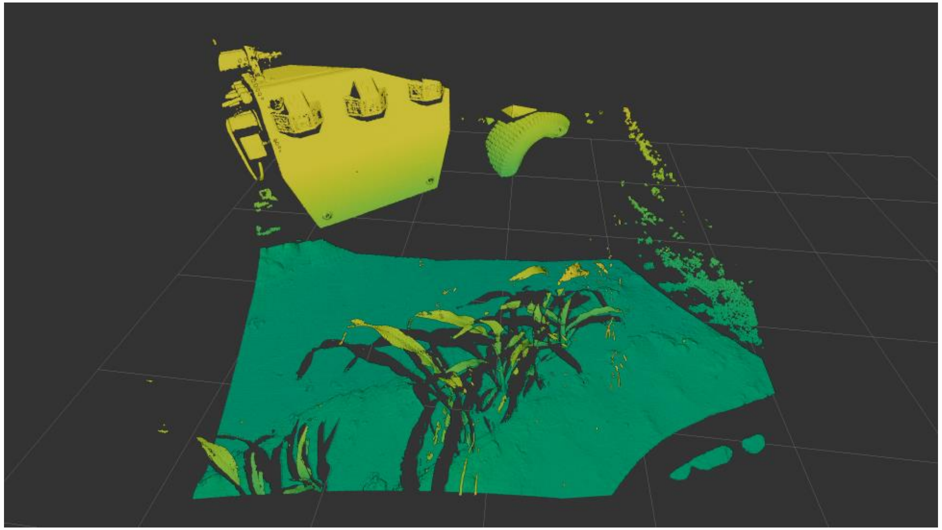


Photoneo

- 3D sensors with millimeter accuracy.

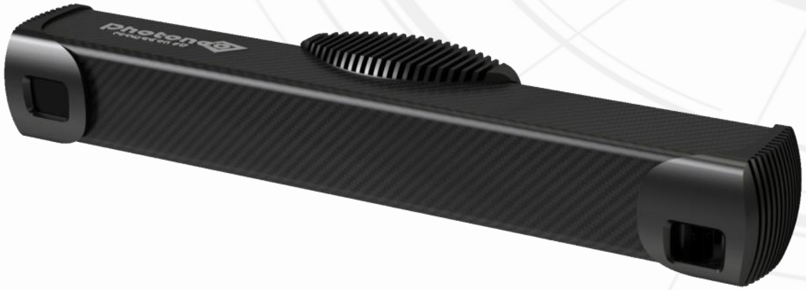


- Nikon RGB



- Photoneo point cloud

Photoneo



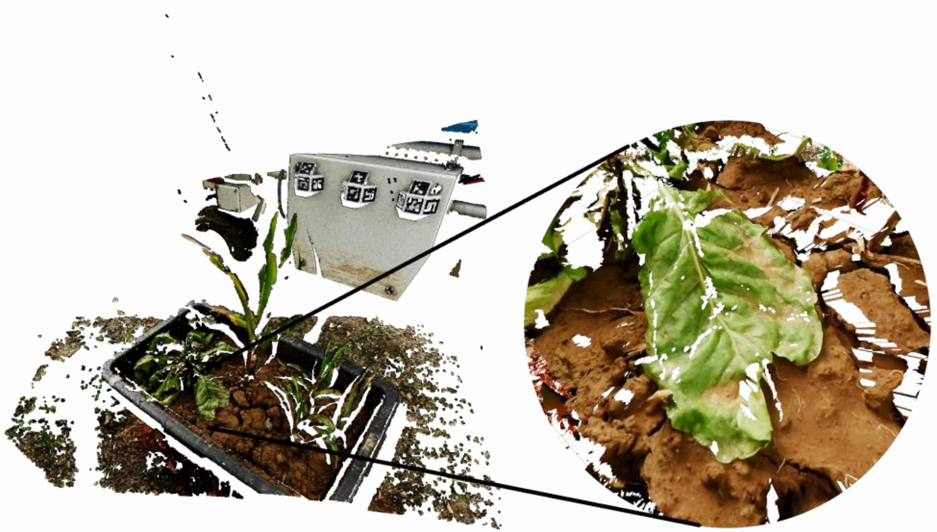
- 3D sensors with millimeter accuracy
- Struggle in strong sunlight
- Emit red visible light while scanning
- Multiple Photoneos cannot scan the same volume simultaneously
- We trigger the Photoneo scanners sequentially

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

- Mesh

- Normals



- Textured mesh

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

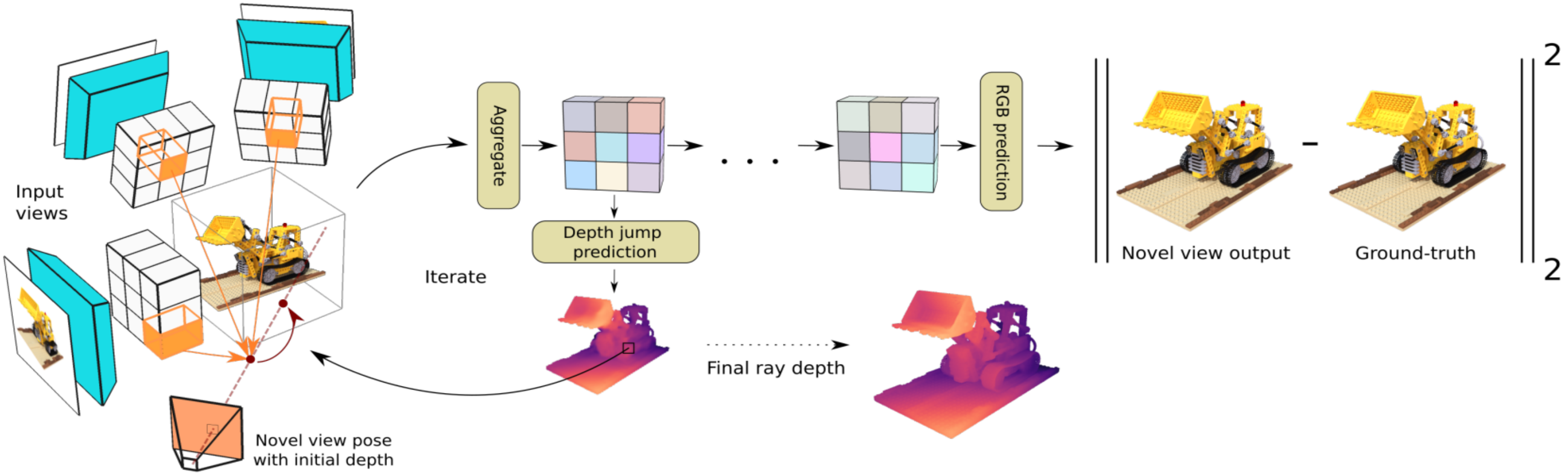
- Hierarchical Deep Stereo (Yang et al.) require supervised training on datasets with ground-truth depth
- Can process only binocular stereo data and not multi-view stereo

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.

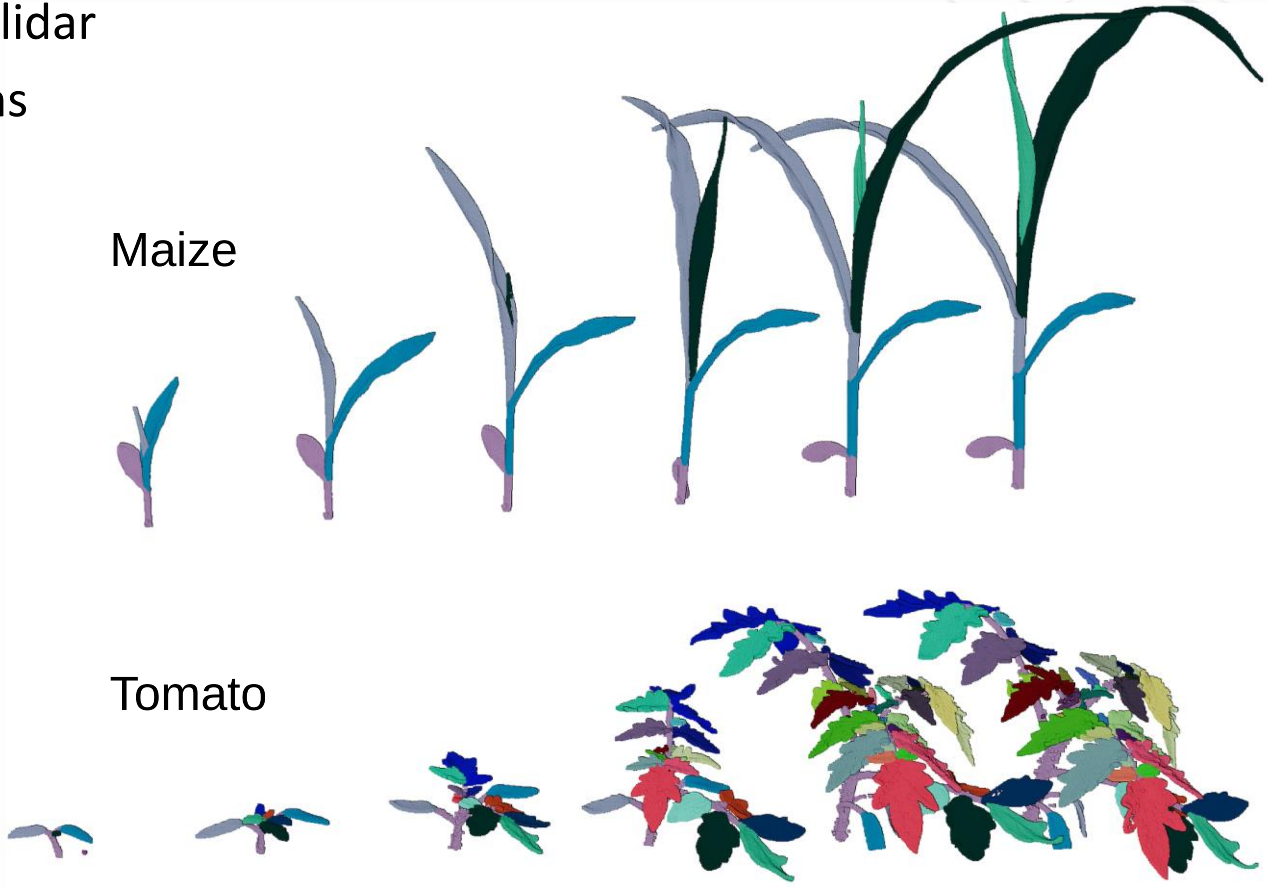


[Rosu and Behnke 2021]

MVS Depth Example Result

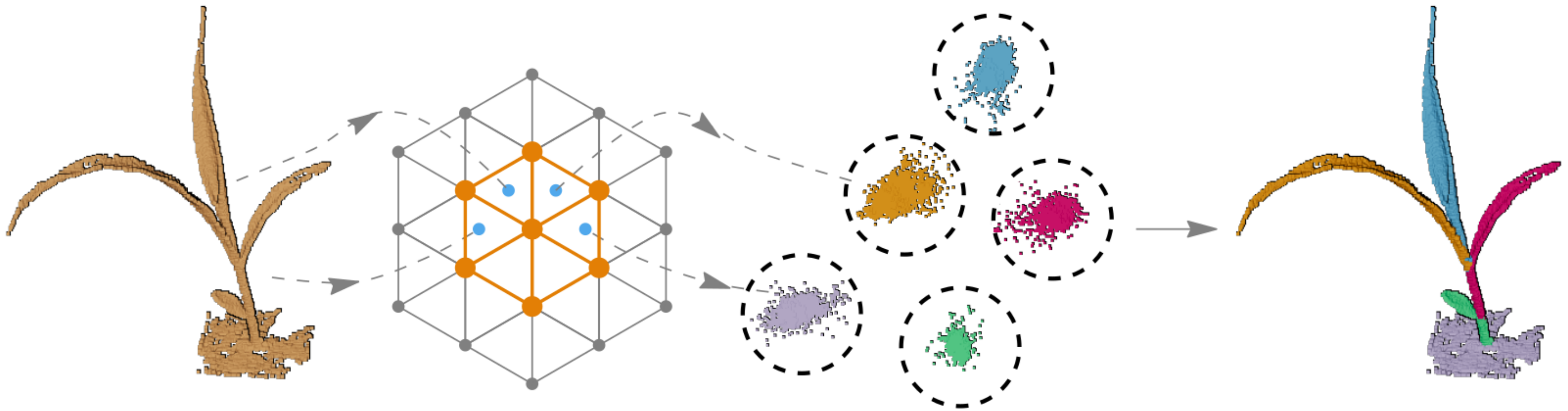
Pheo4D Data Set

- Creted with handheld lidar
- Annotated plant organs
- [Schunck et al.
  PLoS ONE 2021]



Phenotyping: Instance Segmentation

- LatticeNet (Rosu et al.): 3D neural network trained with contrastive loss on Pheno4D data set [Schunck et al. PLoS ONE 2021] performing 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
  - Ligthing
  - 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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