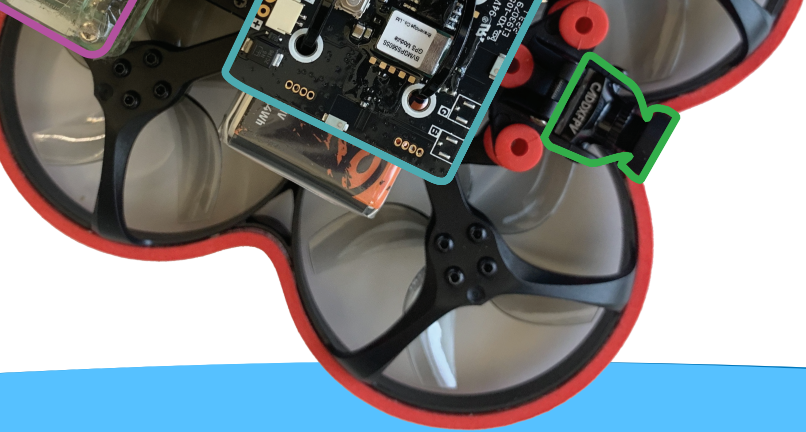

GCCE 2024

Combining Close Range UAVs and Gaussian Splatting for High-Speed Tomato Leaf Size Estimation and Counting

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Muroran Institute of Technology

2024/10/28

stefanbaar.com
github.com/StefanBaar

Research Interests

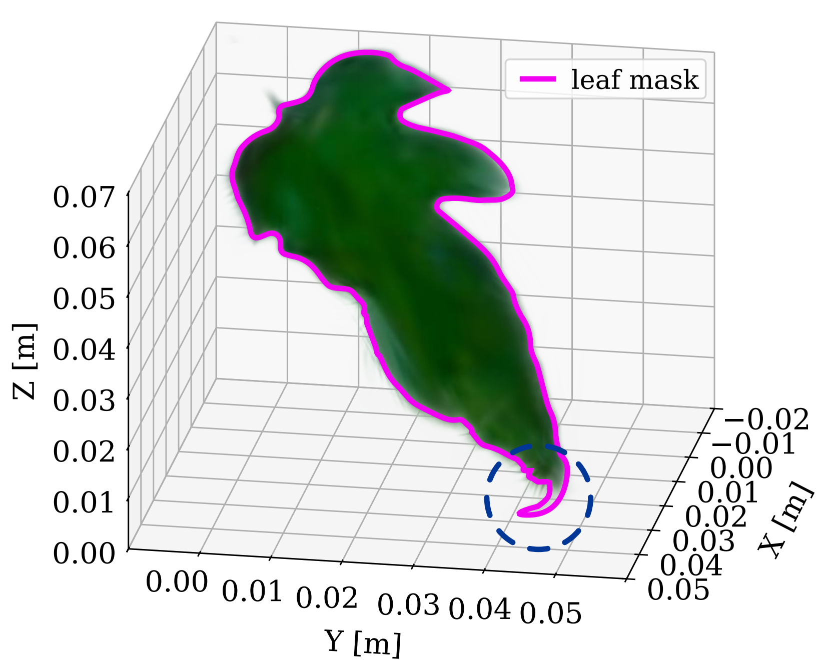
Phenotyping - Computer Vision

- Optimize Environment
- Maximize Fruit Yield

A Leafs GCCE 2024

Today

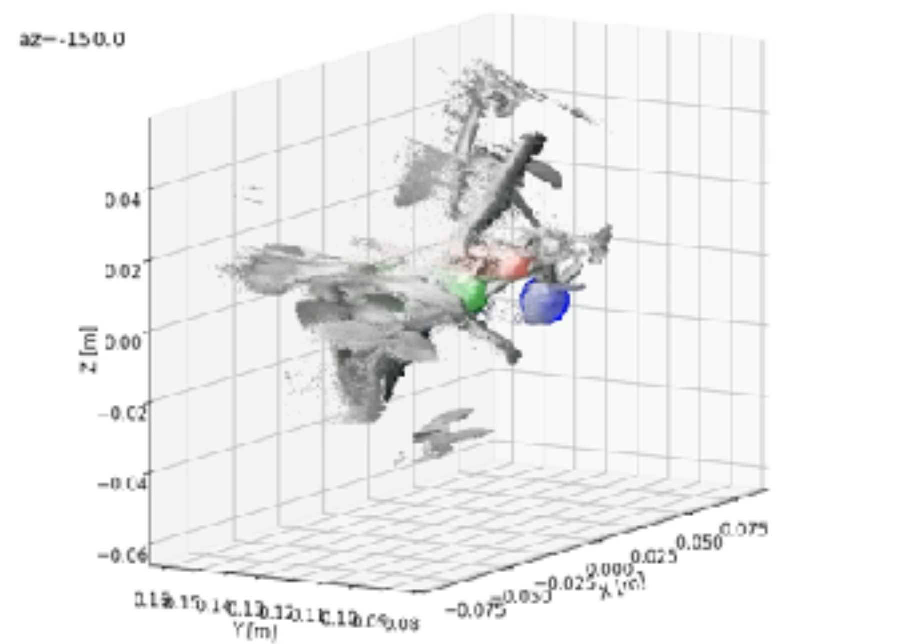
- Leaf **number, area** and **curvature**
- **Drone** based
- **RGB only**



B SCIS/ISIS 2024 Fruits

→ 2024/11/11

- Fruit **number, size** and **shape** + **PREDICTION**
- **Handheld camera** based
- **RGB only**

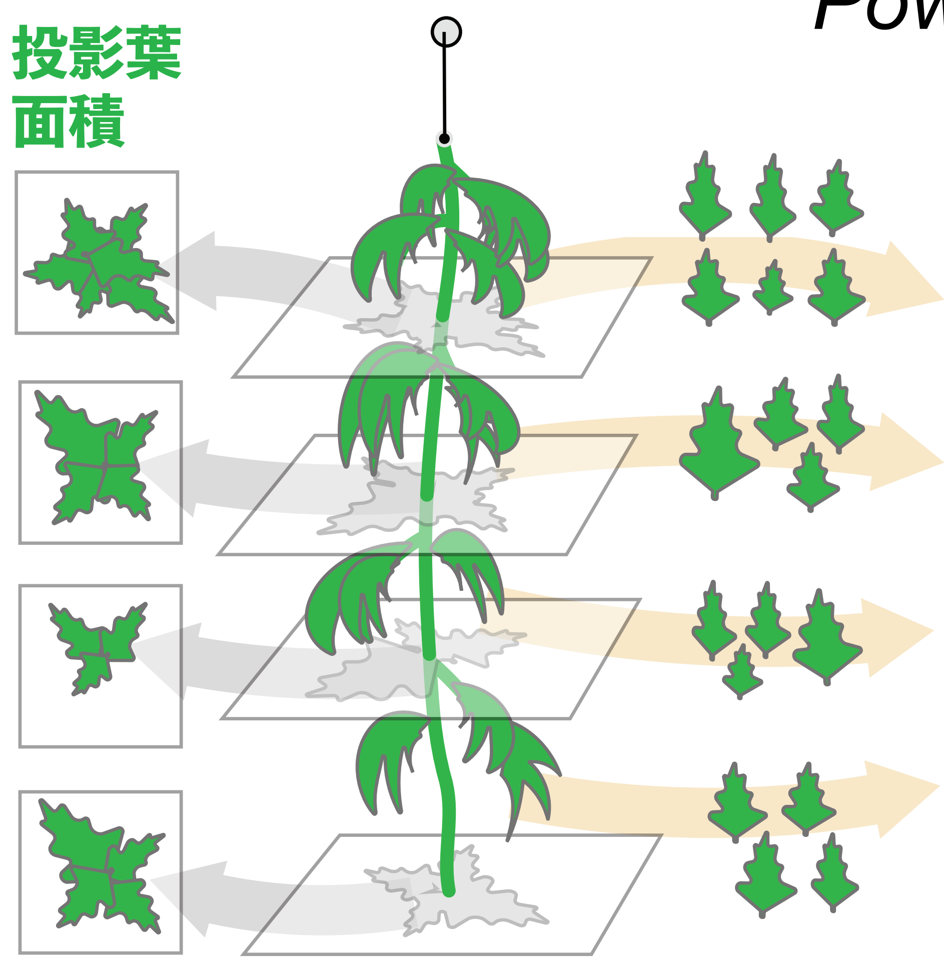


stefanbaar.com

Motivation - Leaf Area Index

Definition and Limitations

How to?



Approximate Light absorption potential

Power Law: $L \sim L_0(1 - e^{-A \times LAI})$

Relationship between:
Light Absorption (L) and Leaf Area Index (LAI)

$$LAI = \frac{\sum_n^N A_{leaf}(n)}{A_{ref}} \approx \frac{\mu(A_{leaf}) \times N}{A_{ref}}$$

Summed Leaf Area   Mean Leaf Area

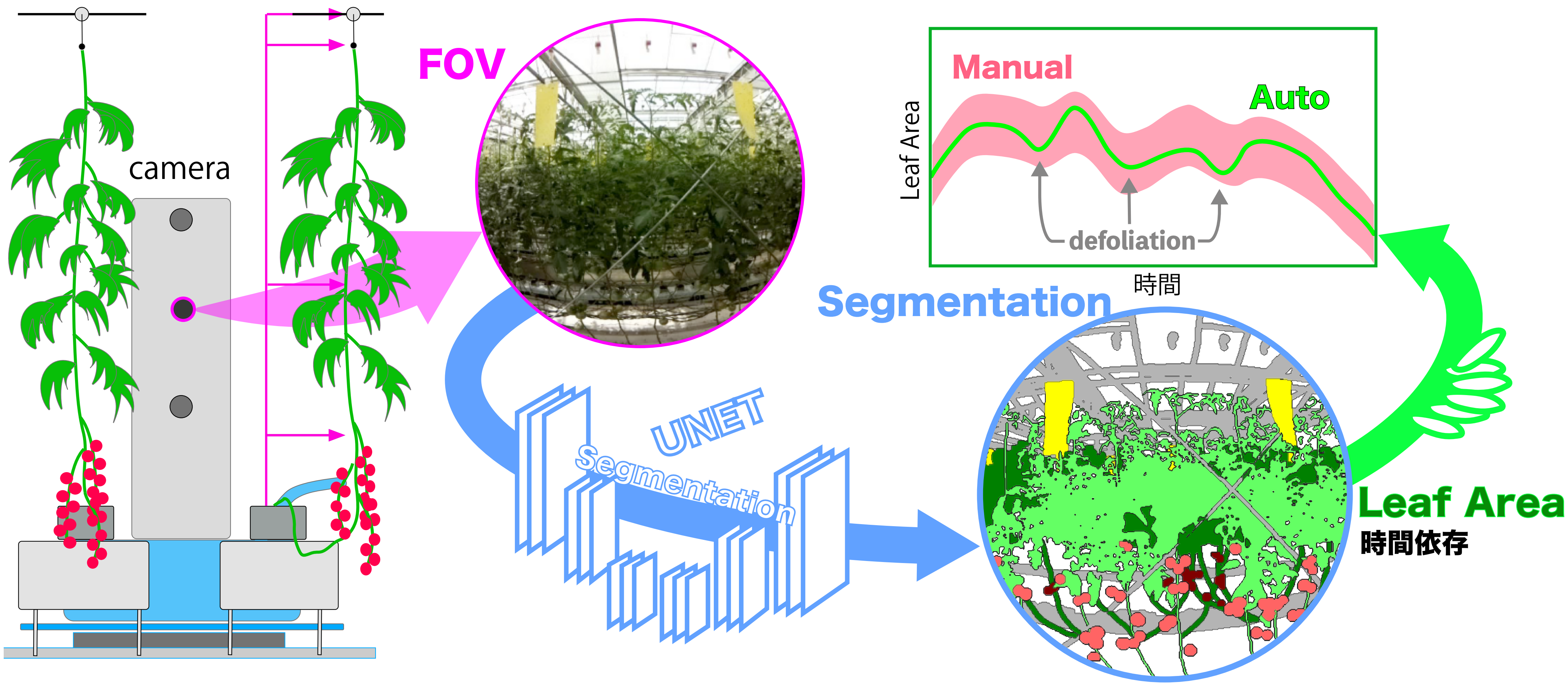
Combined **Leaf Area** (A_{leaf}) per **Reference Area** (A_{ref}).

Motivation - Leaf Area Index

Previous Research

Baar 2022

Goal: Approximate Light absorption potential



$$\frac{dG_p}{dt} = \frac{dLAI}{dt}$$

Approximate LAI by eval. projected leaf area!

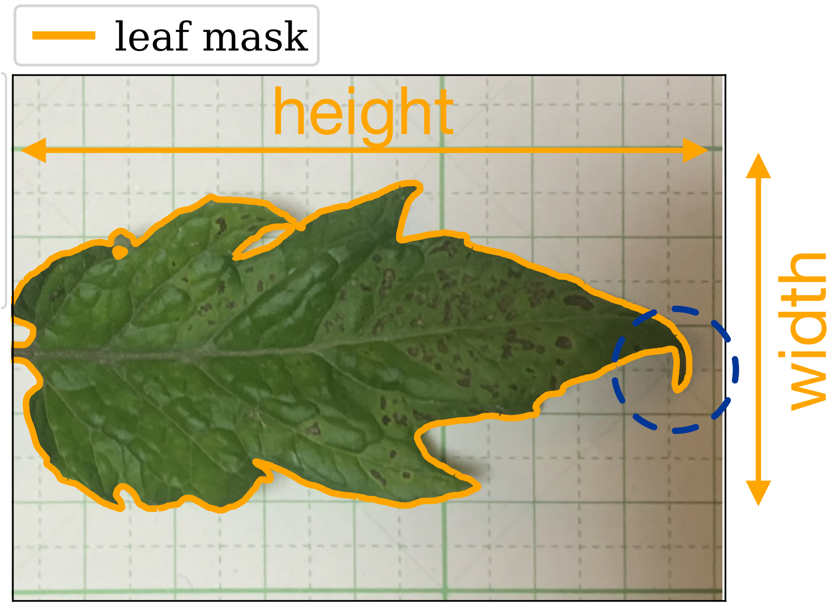
$\longrightarrow$ $LAI = GAIN \times G_p + BIAS$

GAIN and **Bias** have to be calibrated!

Motivation - Leaf Area Index

Definition and Limitations

Goal: Approximate Light absorption potential



Methods:

Imaging - Masking

Projections -> measure **Extinction**

—> Incomplete

(Baar 2022)

Manual leaf measurement

Leaf **No.** and **Area** measurements

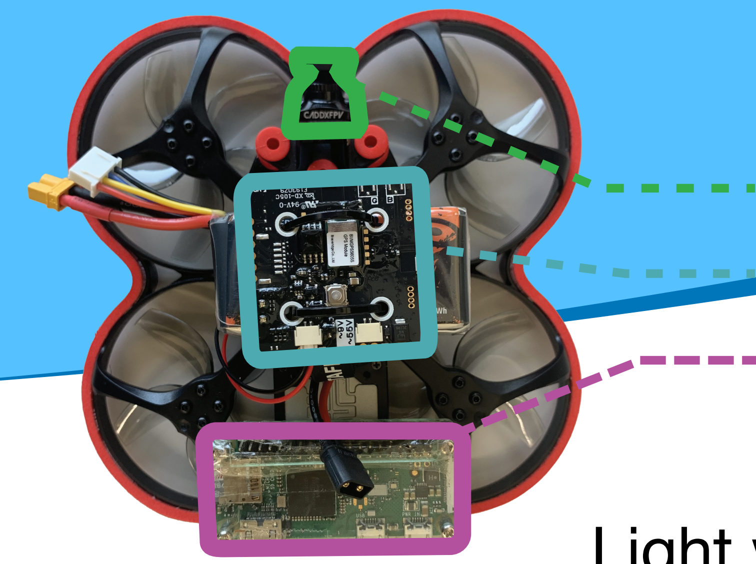
—> low efficiency

Limitations:

No **Shape** and **Orientation** info

Experiment

Drone and Environment



Light weight ~ 100g
Area: 6cm x 6cm
Small Battery: 450mAh

Goal:

- **Monitor Tomato Plant**
- **Time series observation**
  - **Leaf number**
  - **Leaf area**
  - **Leaf curvature**

Optimize: - environment
- defoliation

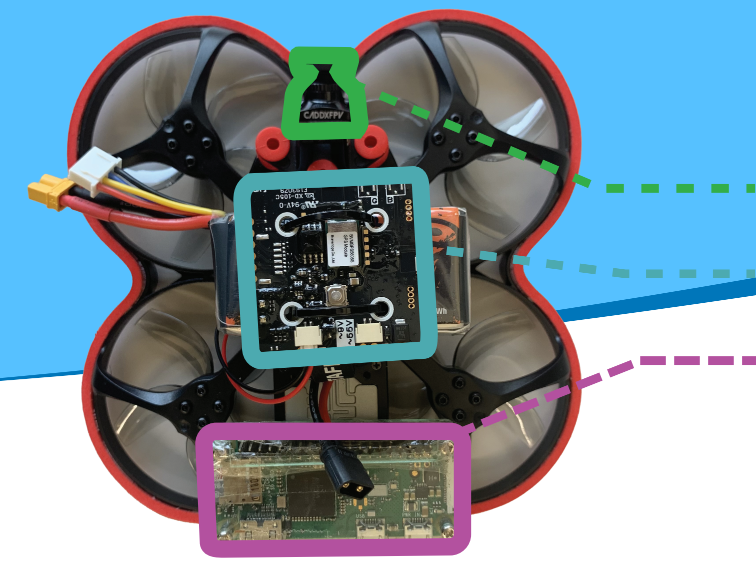
- controll via wifi
  - **Drone Bridge :** https://GitHub.com/DroneBridge/DroneBridge
  - **ez-wifibroadcast :** https://github.com/rodizio1/EZ-WifiBroadcast
  - **OpenHD :** https://openhd.gitbook.io/open-had
  - **Ruby FPV :** https://RubyFPV.com

Guided Flight: Work in progress!
Via Ground pattern Reference

Not in this talk!

Experiment

General Idea



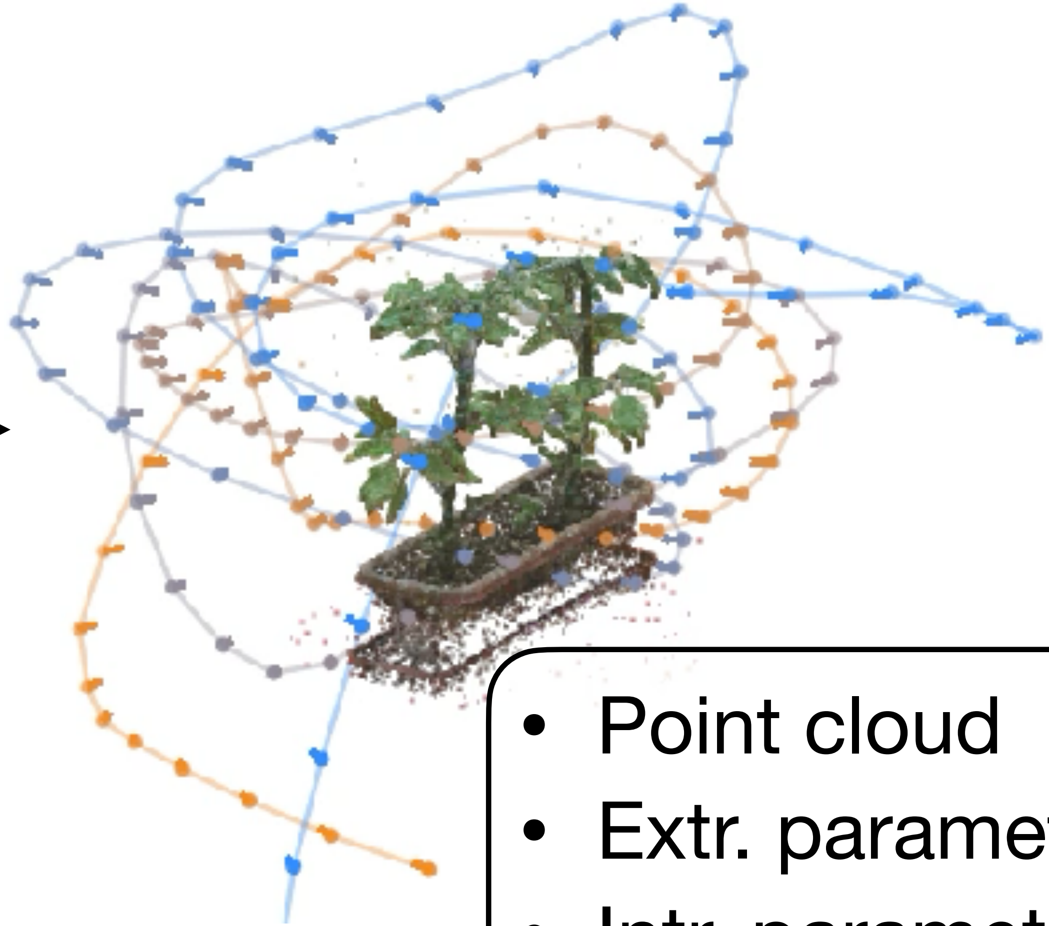
This study:

Input
RGB video

Output
3D model

Test Environment

SfM →

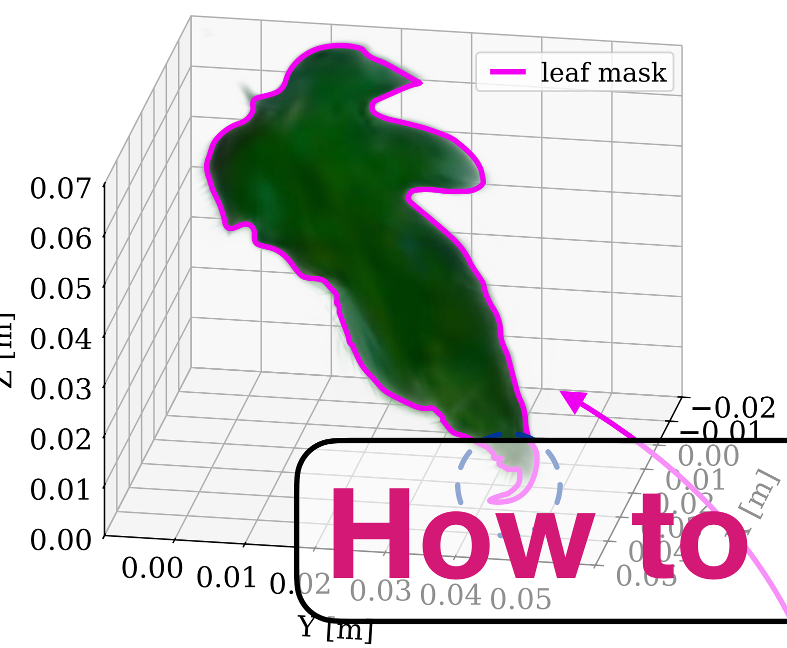


- Point cloud
- Extr. parameter
- Intr. parameter

Greenhouse Environment in later phase

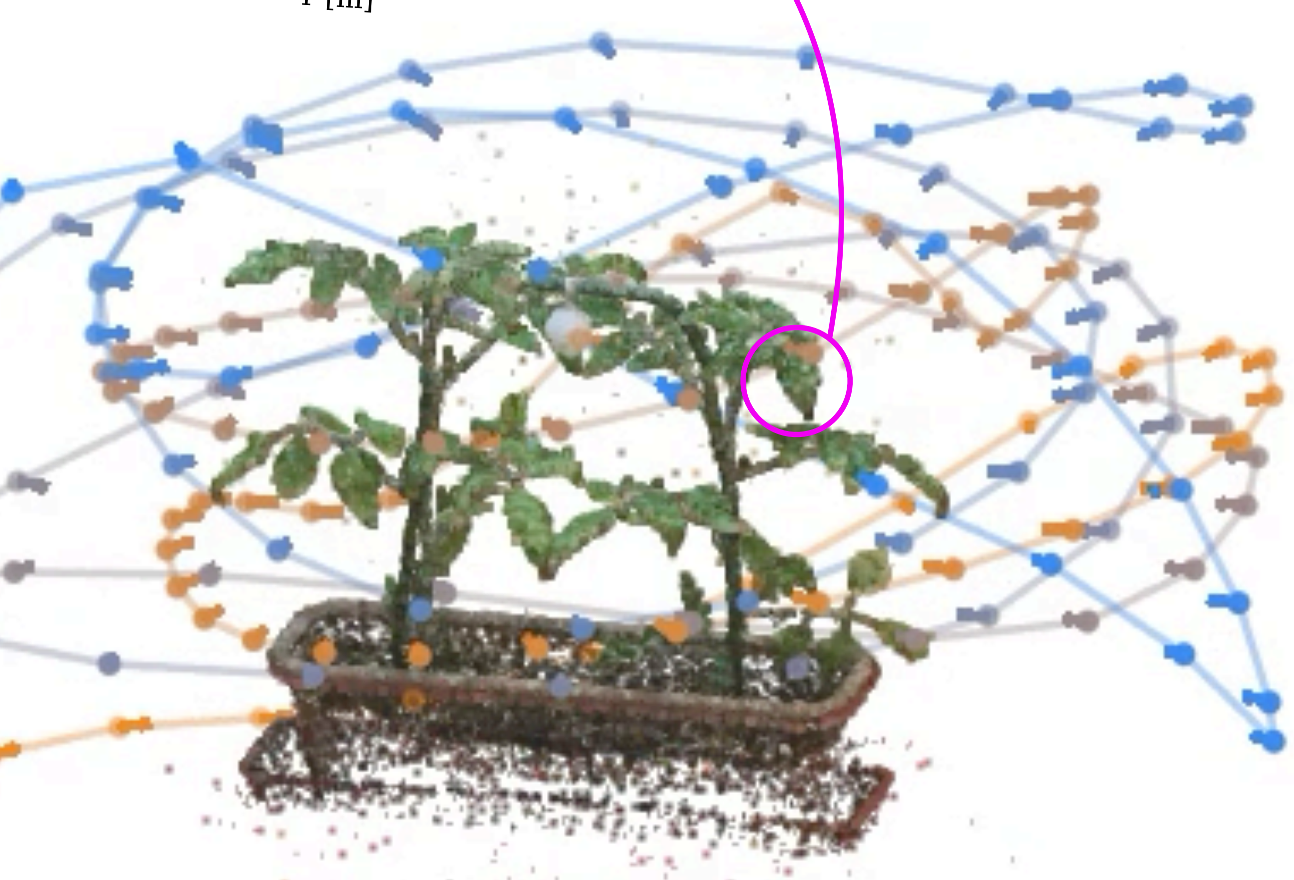
Data Reduction

Overview



Single Leaf
- **Area**
- Curvature
- Number

How to measure?



3D Leaf segementation - Methods

A) Frame accumulation

Semi-automated UAV → **Spiral Scan**

B) 3D - Reconstruction

1 **Features**
hloc-super glue → Tasks: feature extraction, feature matching, bundle adjustment

2 **SfM model**
Gaussian-Splatting → Results: **3D Splats**

3 **Metric Calibration**
Reference Sphere → Results: **Camera parameters**

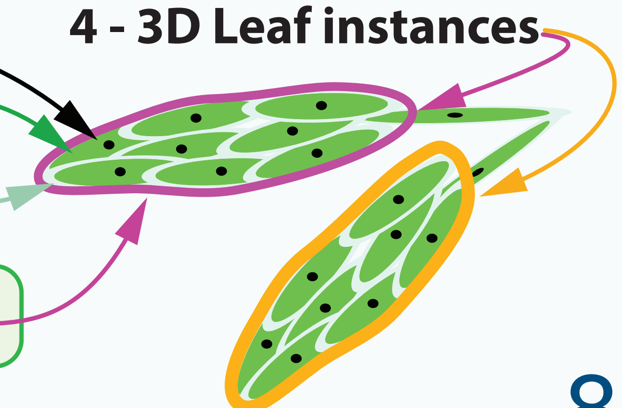
C) Leaf segmentation

1 **color & symmetry** → Plant <-> BKG
2 **Pointnet++** → Leaf <-> Stem
3 **Mean Shift** → Leaf index

D) Leaf Manifold estimation

1 Point-Cloud + Gaussian features
2 Probability mapping
3 Connected Components

4 - 3D Leaf instances



Metric Calibration

Motivation - Related research

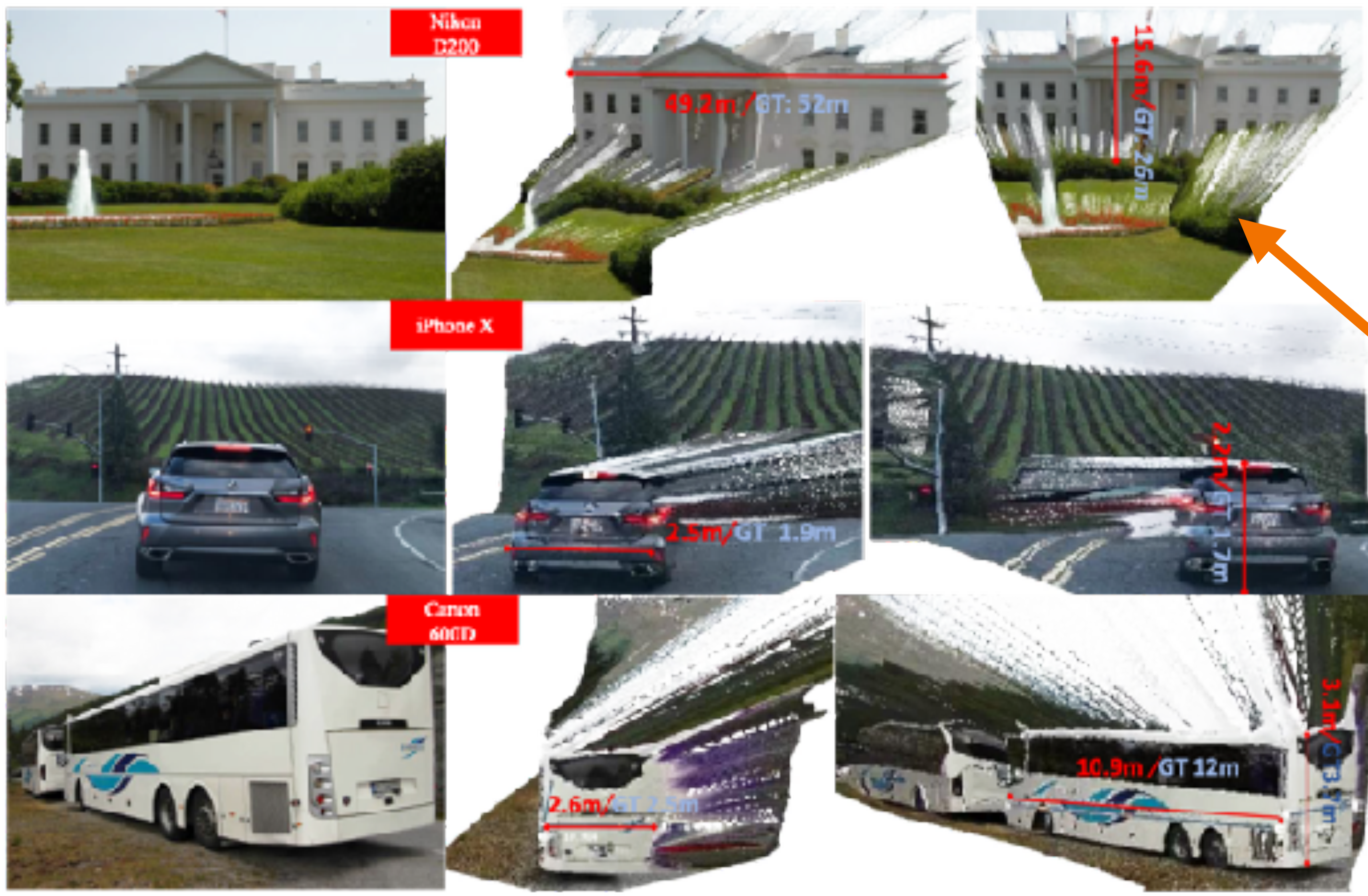


Fig. 14 – Metrology of in-the-wild scenes. We collect several Flickr photos, which are captured by various cameras. With photos' metadata, we reconstruct the 3D metric shape and measure structures' sizes. Red and blue marks are ours and ground-truth sizes respectively.

(Hu 2024)

Size from Single Image

Metric3D v2: A Versatile **Monocular Geometric** Foundation Model for Zero-shot Metric Depth and Surface Normal Estimation

- **Projections not correct**
- **Metric unreliable**

Not possible!

↓

Need Reference

Metric Calibration

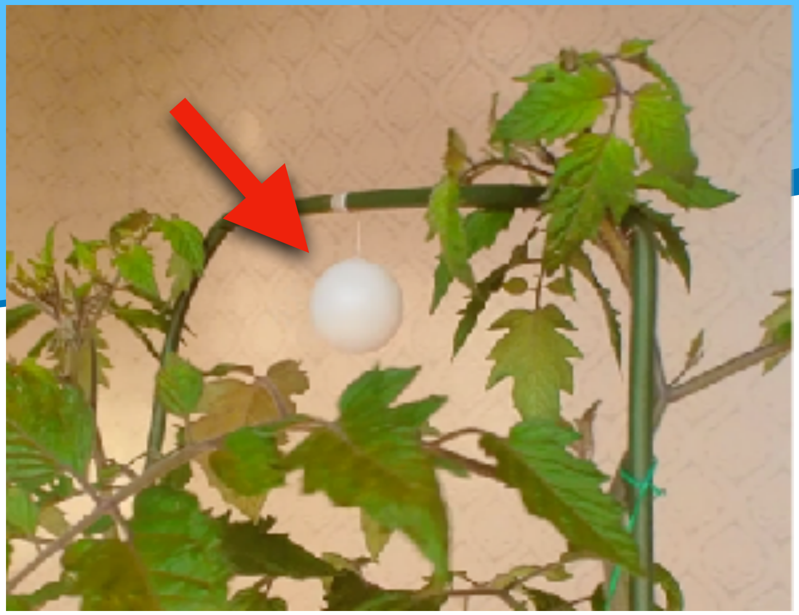
Motivation

- Image coordinates are in R2 (unit pixel)
- Relationship to real world dimensions are unknown.
- Need to find metric **g**

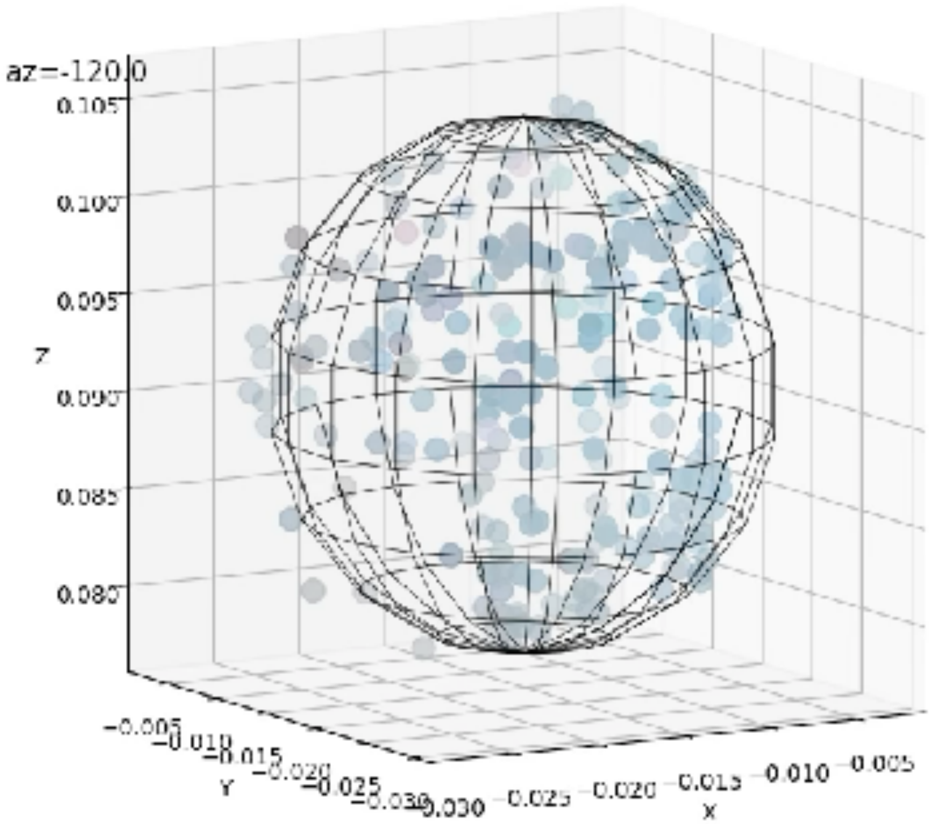
$$\mathbf{S} = \mathbf{g}\mathbf{B}$$

$$\mathbf{B} = (\vec{b}_1, \vec{b}_2, \vec{b}_3)$$ Uncal. Basis

$$\mathbf{S} = (\vec{s}_1, \vec{s}_2, \vec{s}_3)$$ Metric Basis

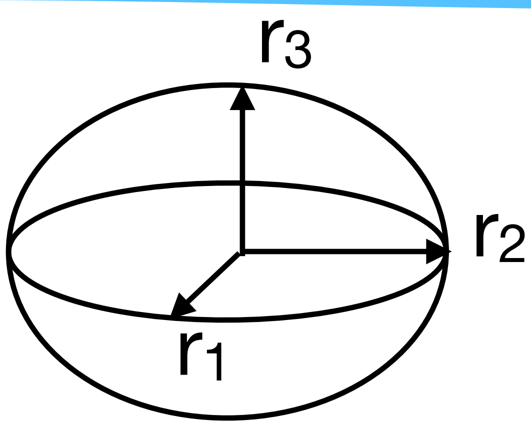


Calibrator (ref. Object)



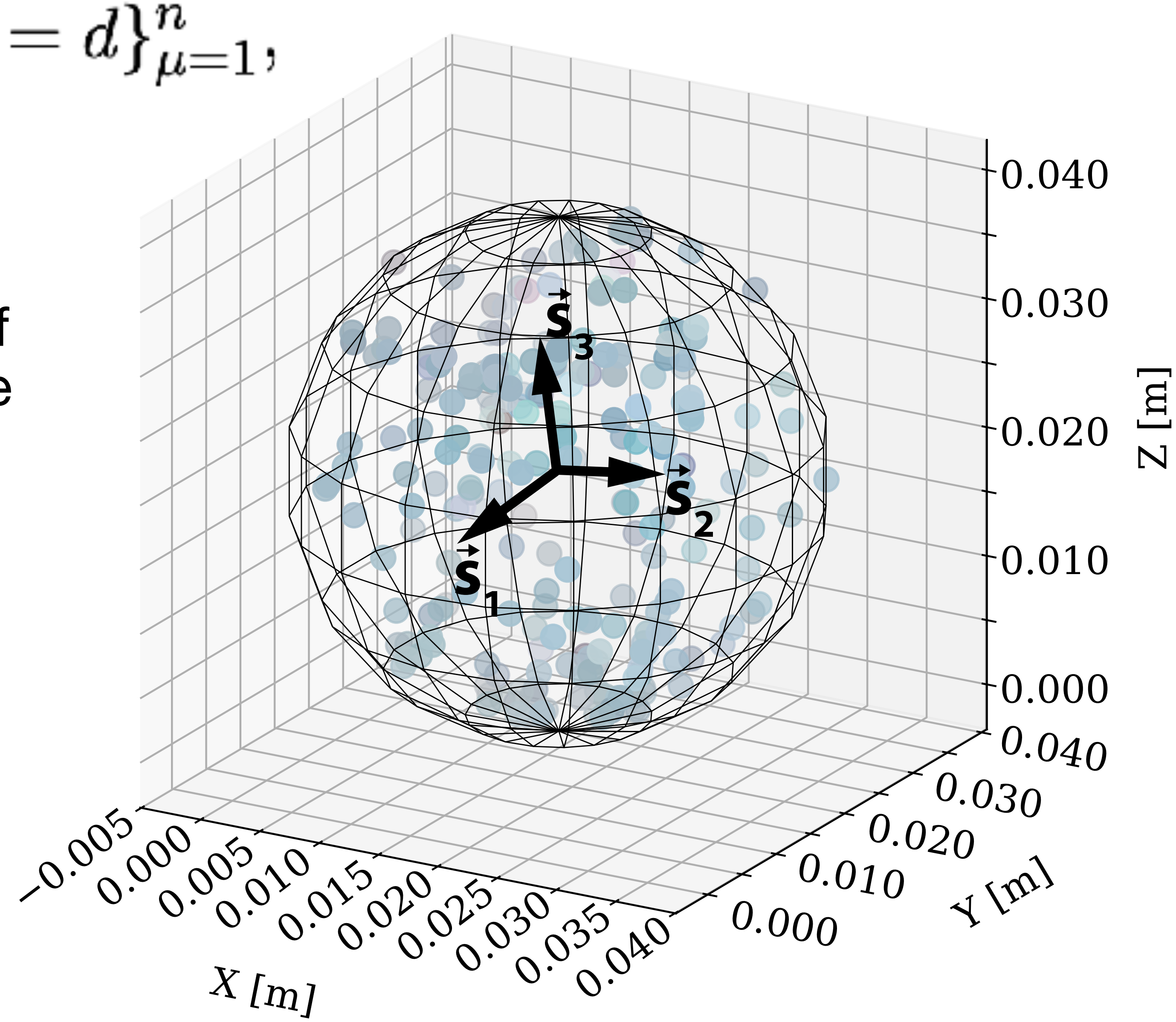
Metric Calibration

Calibrator



$$(\mathrm{P}) : \begin{cases} \{\mathbf{x}_\mu^\top \mathbf{S} \mathbf{x}_\mu = d\}_{\mu=1}^n, \\ \mathbf{S} \succeq 0, \end{cases}$$

Calibrator (ref. Object)



Eigenvectors of S give the directions of the principal axes of the ellipsoid, while its eigenvalues $(\lambda_i)^d$ are related to the lengths (r_i) of its principal (semi-)axes by

$$r = \sqrt{d}\lambda^{-1/2}.$$

Table 2: **Metric**

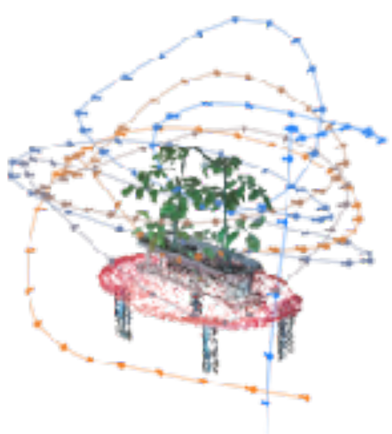
method	g_{11}	g_{22}	g_{33}
splatfacto	1.56	1.49	1.45
nerfacto	1.58	1.52	1.44

Leaf Segmentation

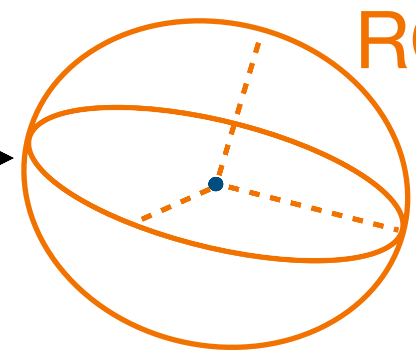
Background separation

Symmetry Segmentation

Camera trajectory —> centre and major axises



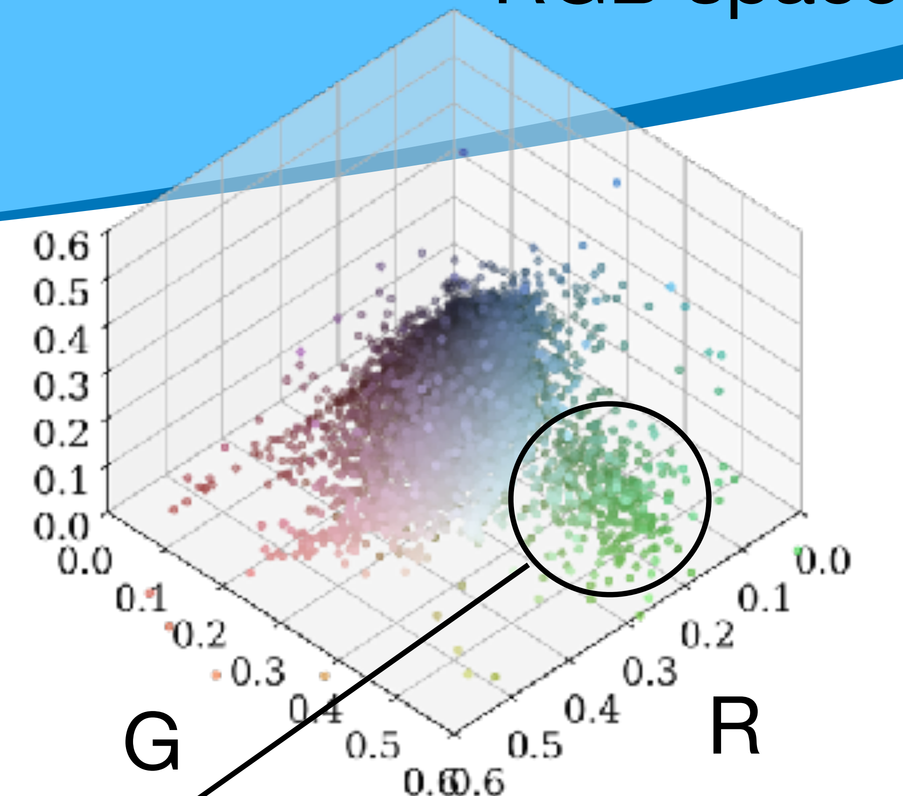
SVD

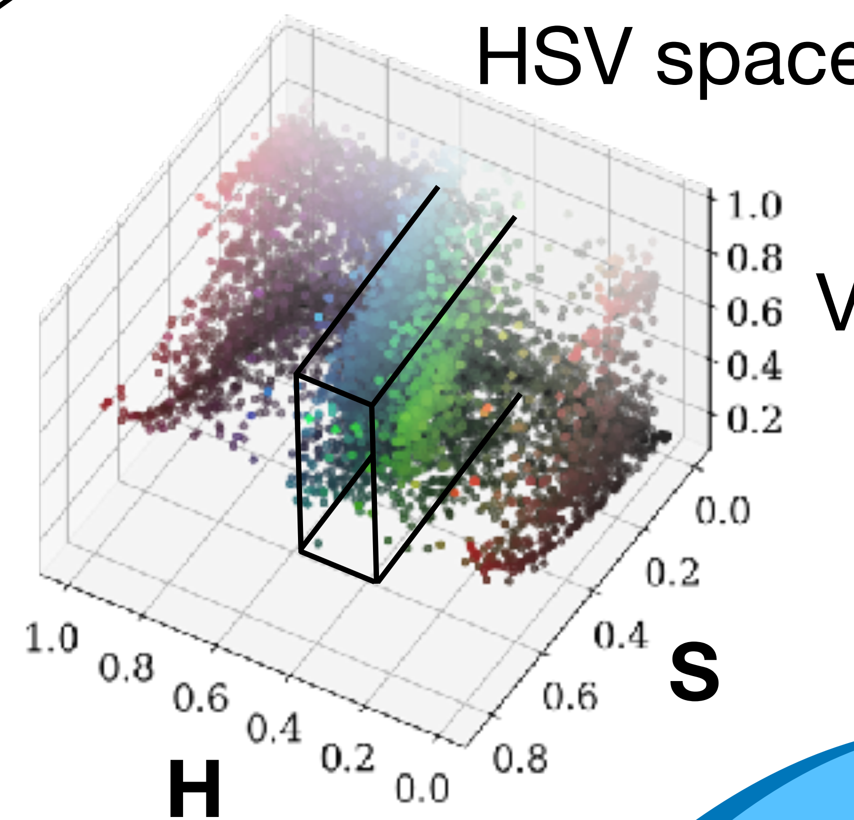


Color Segmentation

sparse

dense



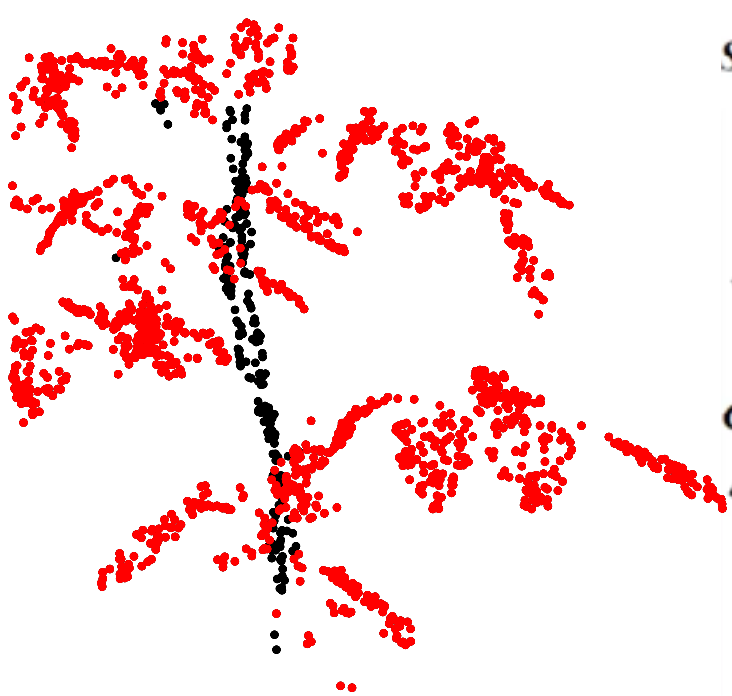


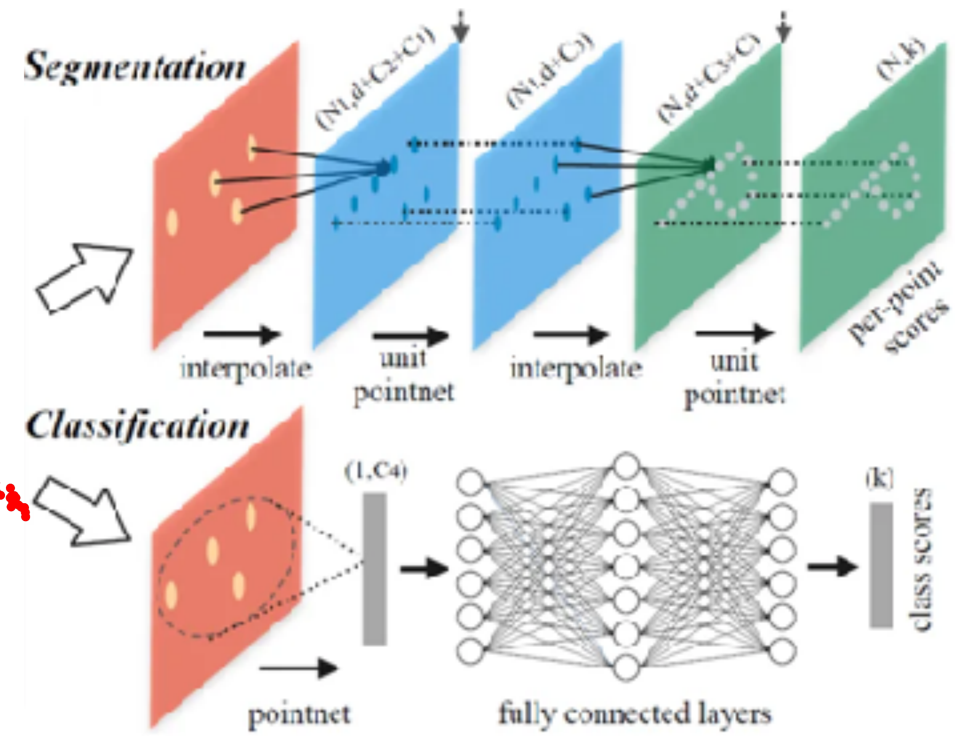
Leaf Segmentation

Counting and separation

Stem - **Leaf** classification

Leaf instance segmentation





Pointnet++ (Pre-trained: Li 2023)

- not scale invariant
- Fixed point No. (1024, 2048, etc)
  - scales with memory

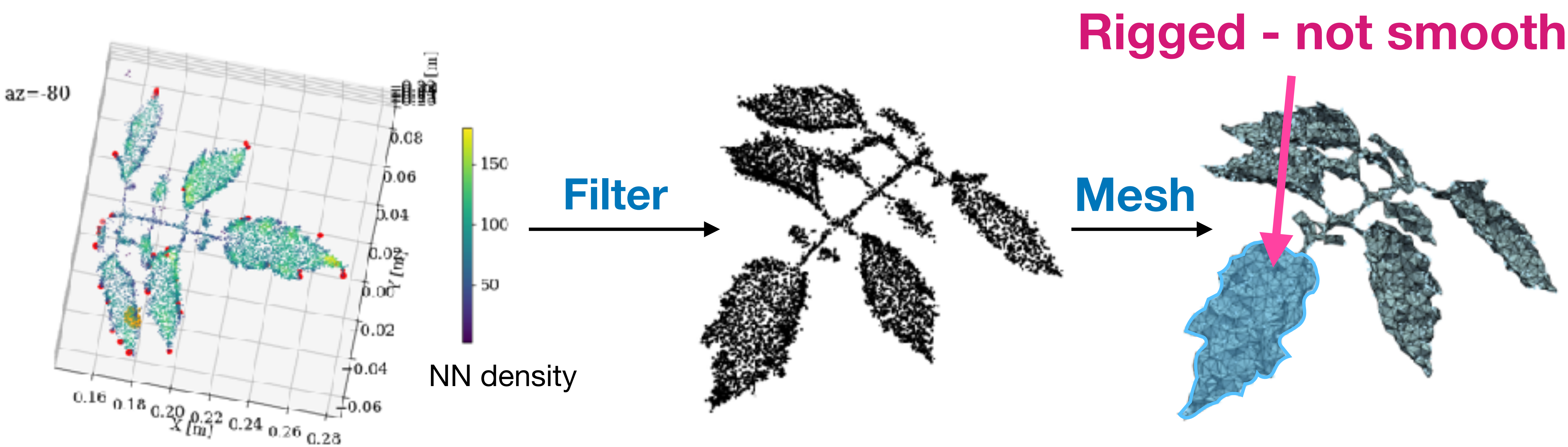
Mean-Shift (sk-learn)

- Requires **Leaf size** (bandwidth) est. ← **Metric**
- Probability density

Leaf Area Estimation

Point cloud to Mesh

Area estimation, requires smooth surface reconstructions



ShrinkWrapping

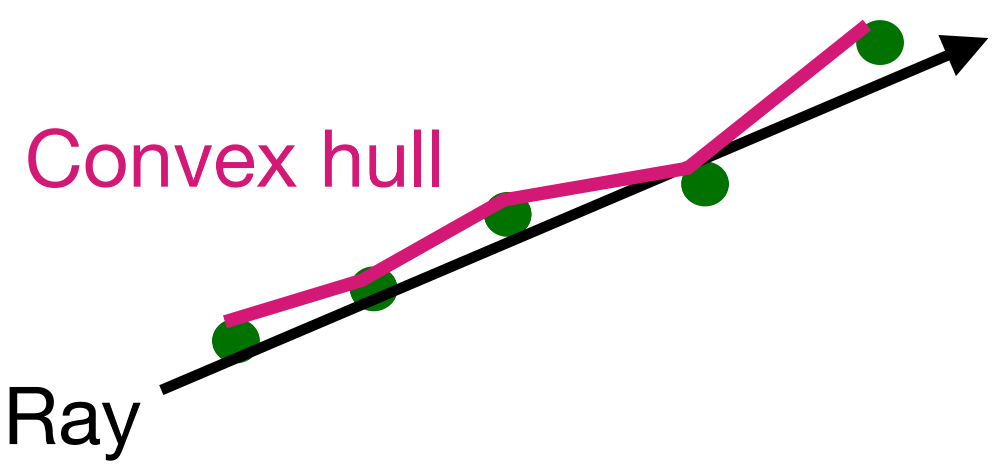
- Point2Mesh (Hanocka 2022)
- Watertight Manifold (Huang 2018)
- Shape As Points (SAP) (Peng 2021)

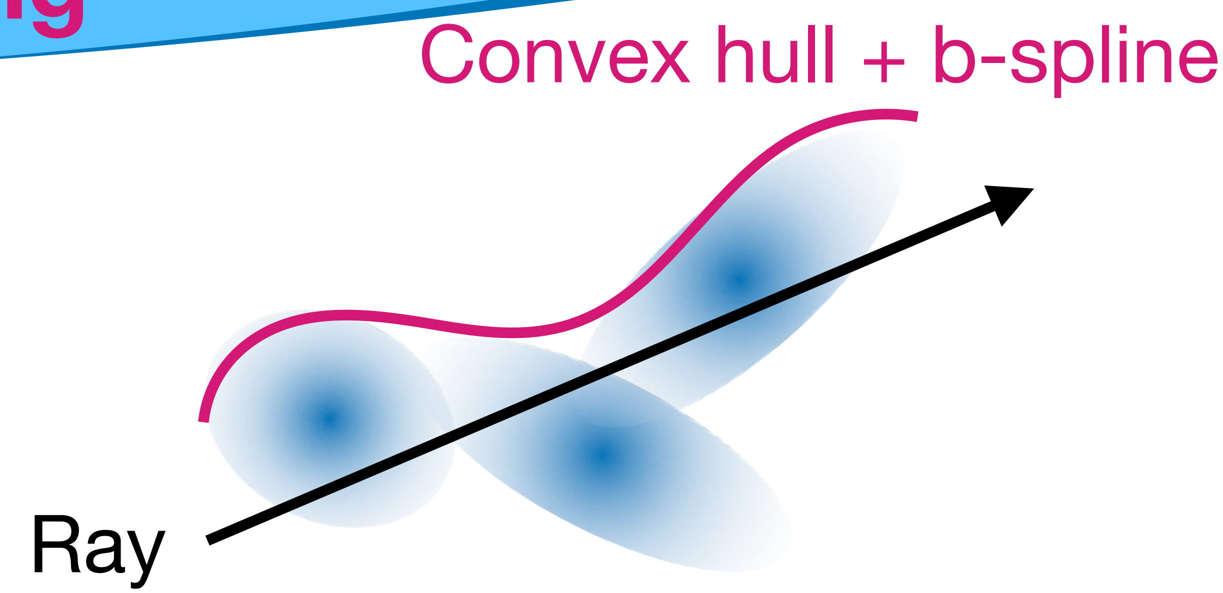
Methods:

(XYZ - Point clouds)

Model Representation

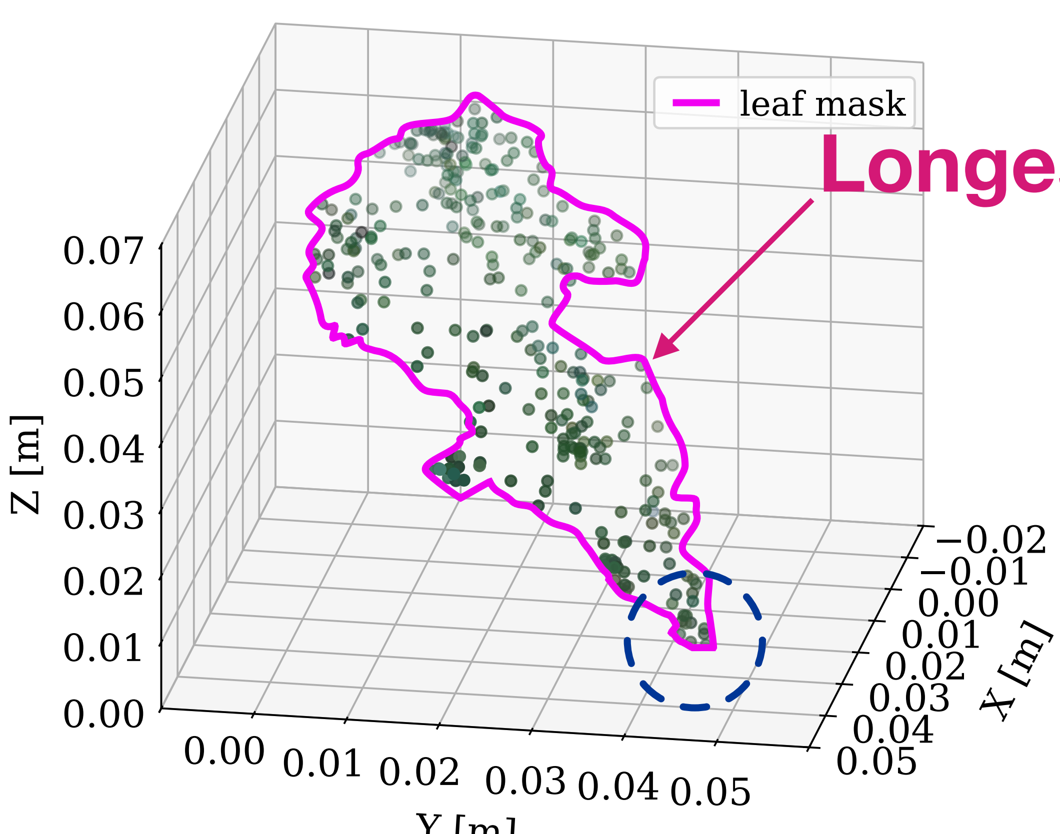
Nerf vs. Gaussian Splatting



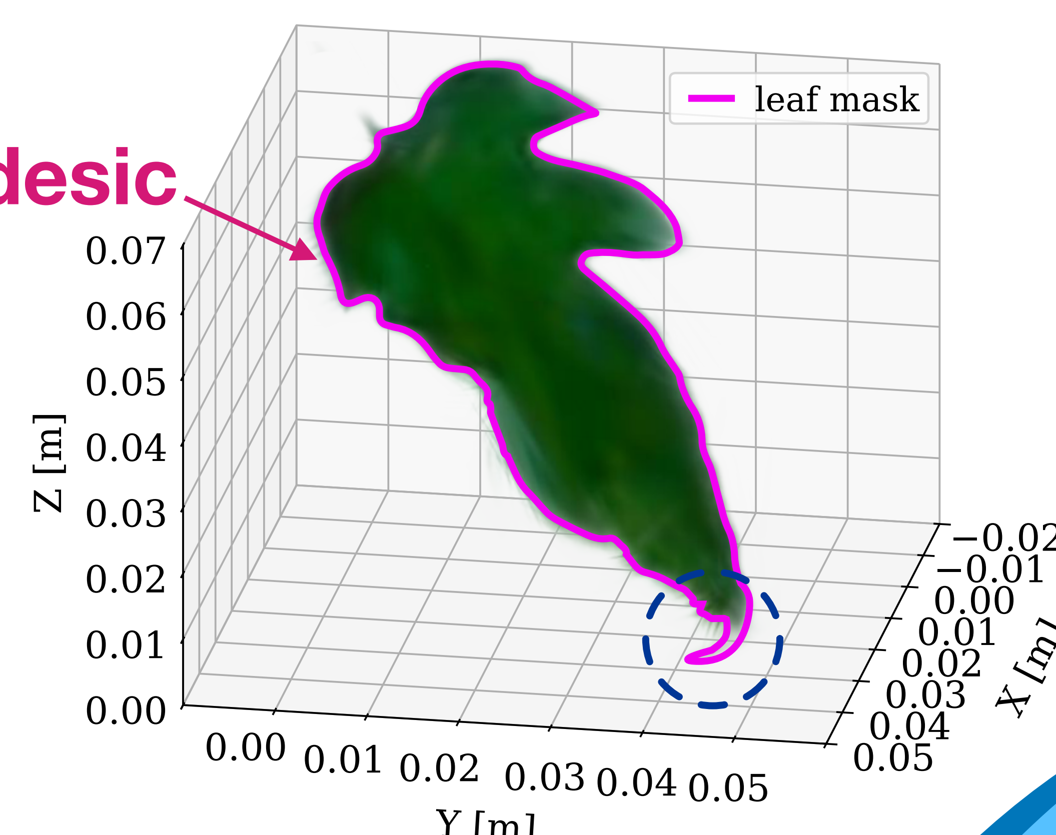


NERF (Neural Radiance Fields)

Gaussian Splatting



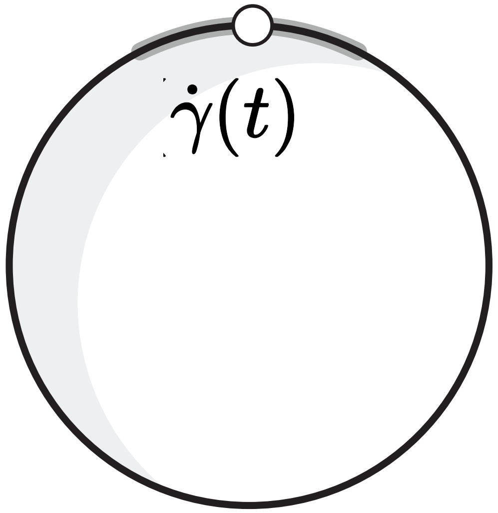
Longest Geodesic

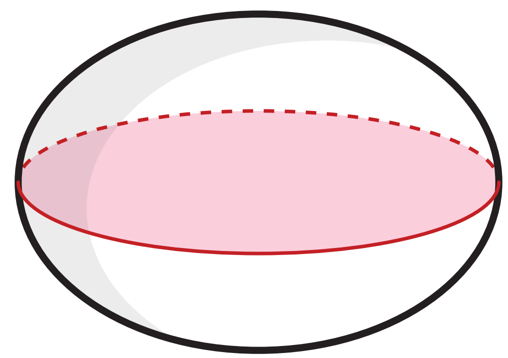


Curvature Analysis

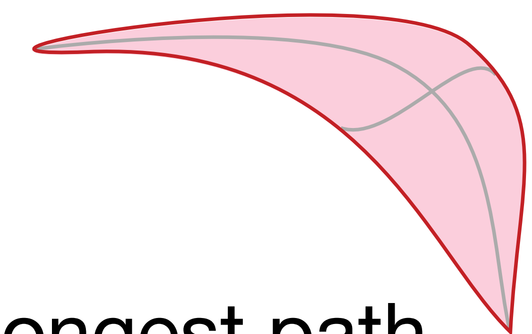
Riemannian curvature

Local Curvature





R2 Geodesic (**E**) in R3



Longest path

In a Riemannian manifold M with metric tensor g, the length L of a continuously differentiable curve γ : [a,b] → M

$$E(\gamma) = \frac{1}{2}\int_a^b g_{\gamma(t)}(\dot{\gamma}(t), \dot{\gamma}(t))\, dt.$$

- Fit wedge (R2) to R3 surface enclosed by **E** (R2)
- Measure Leaf curvature

Indicate Leaf stress

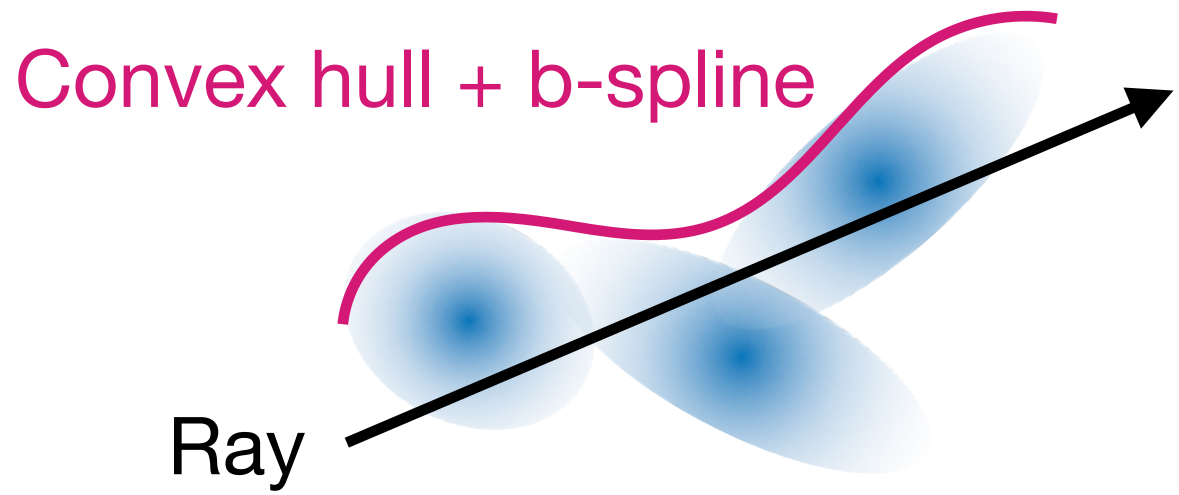
Leaf Area Estimation

Point cloud to Mesh

Area estimation, requires smooth surface reconstructions

Nerf

Gaussian Splatting



Methods:

XYZ - Point clouds

+ spherical harmonics

+ 12d gaussian

Estimate NN. Connections from gaussians

GS Surface Reconstruction

- gs2mesh (Wolf 2024)
- SuGar (Guedon 2024)
- Gaussian Opacity Fields (Yu 2024)

Results

Experimental Setup

Table 1: **Measurement Methods**

	camera	resolution	FPS	bit rate	method	velocity
A	insta360 Go2	2K	50	50 bps	UAV	12m/s
A	Caddx vista	720p	30	50 bps	UAV	12m/s
B	IPhone X	720p	24	50 bps	hh. video	6 m/s
C	IPhone X	4K	1	-	hh. still	-

A UAV video

B Handheld video

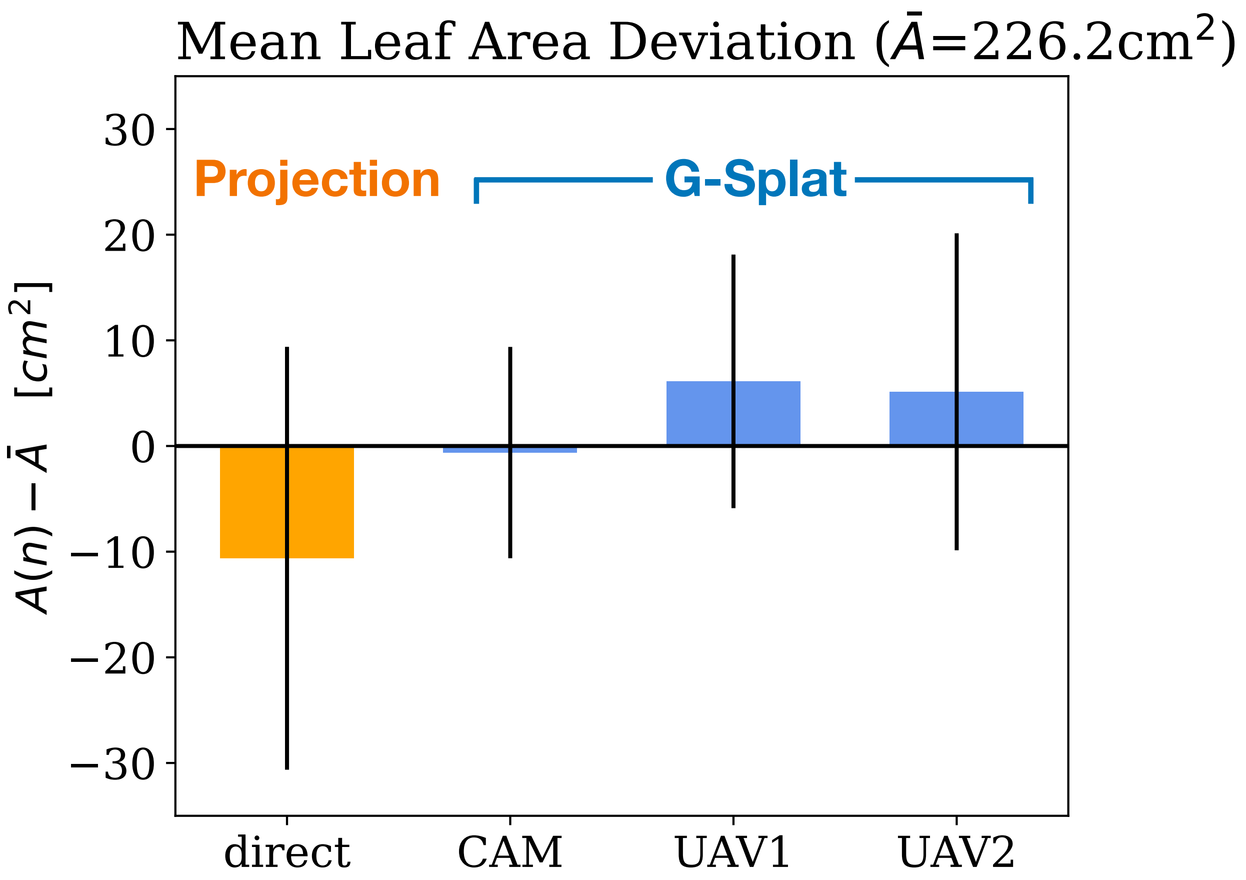
C Still image

- A-B Varying trajectory (extrinsic parameters)
- Intrinsic parameters

Results

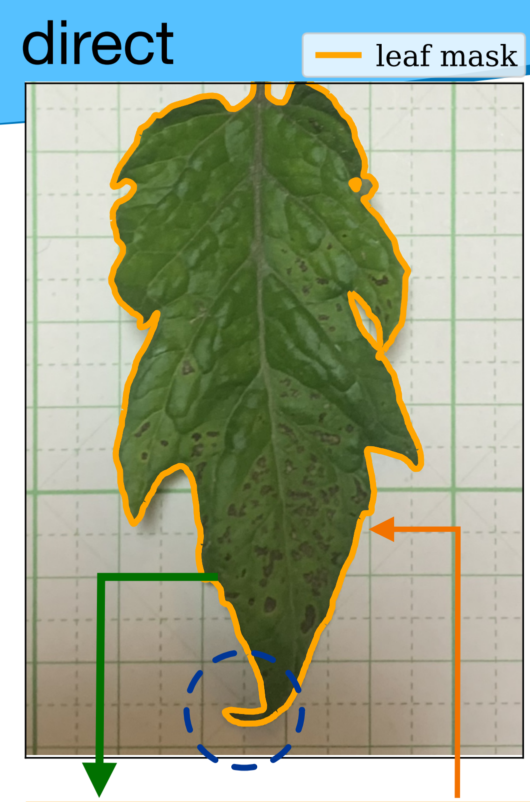
Single Leaf Area

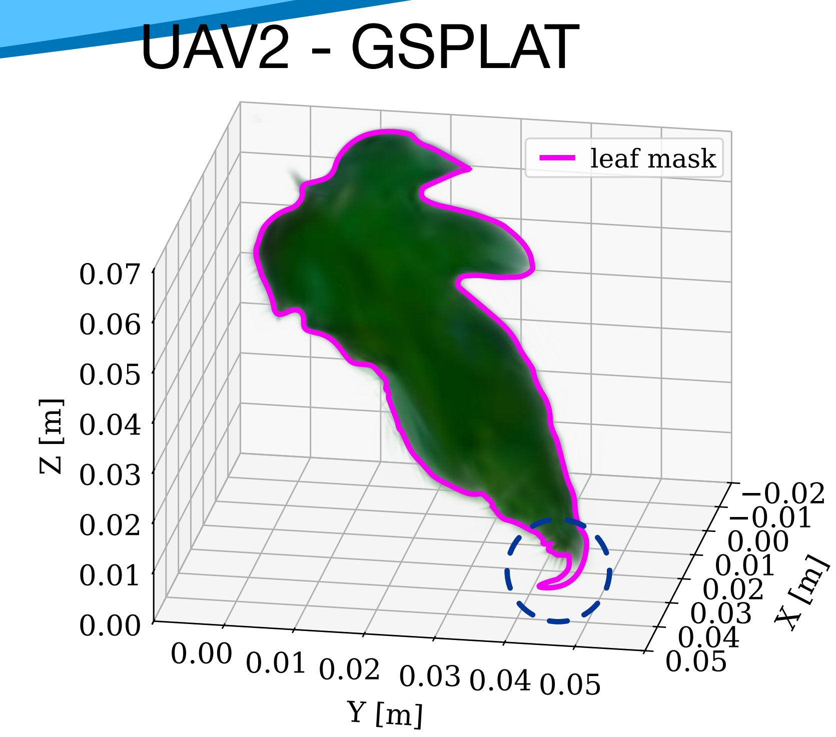
- High Ground Truth variance
- Results vary by 5~10%

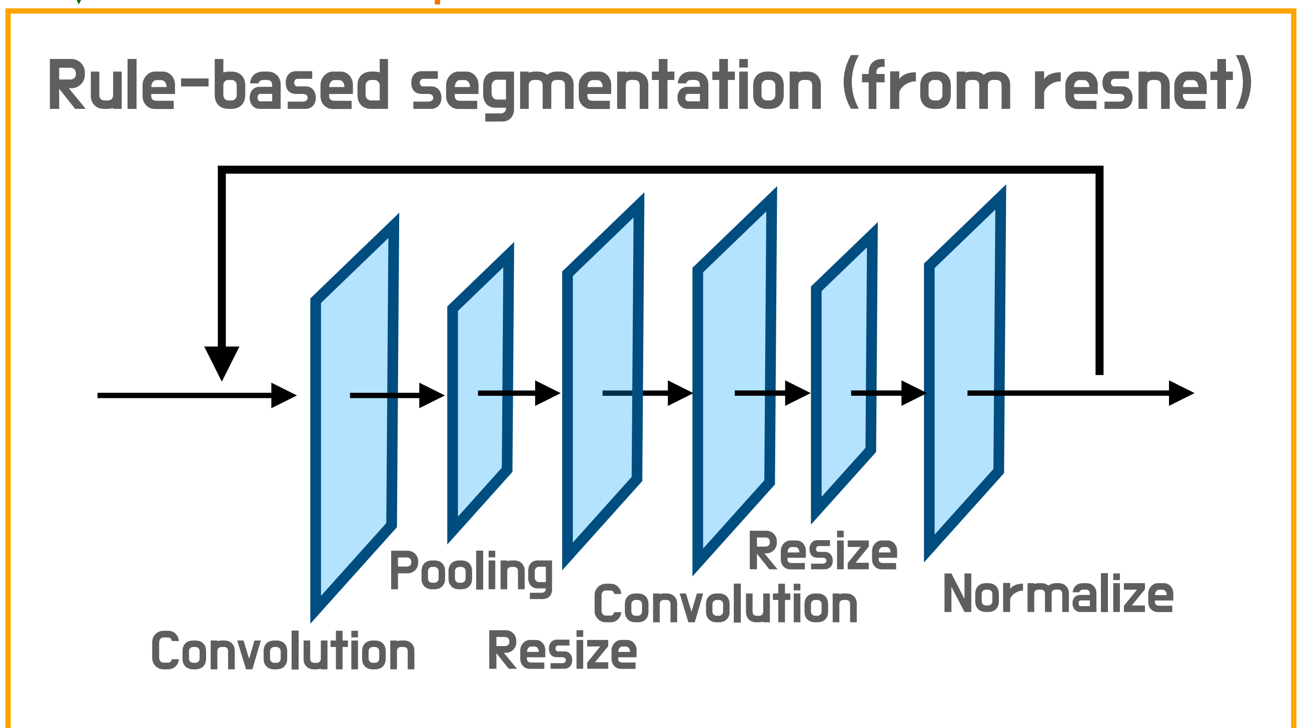


- higher resolution
- Lower noise
- **Larger FOV**
- **Worse intrinsic para.**

→ Higher variance







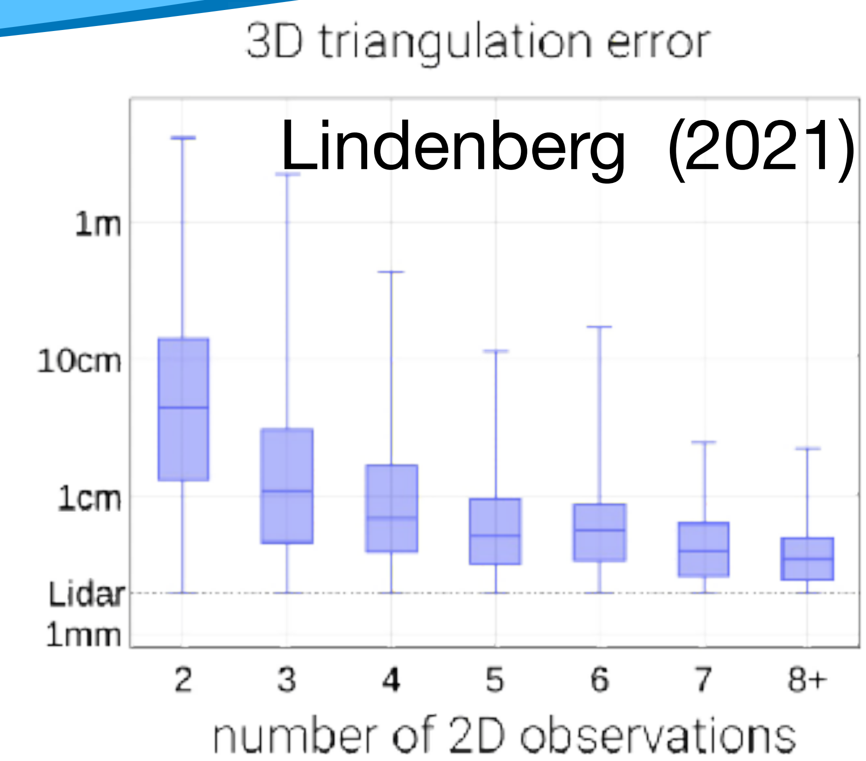
Discussion

Fun but not efficient

What we have learned

Precise 3D structures from videos

- Req. **low** brightness contrast
  - Avoid shadows and highligths
- **high** colour contrast
- Proper white balance



Problems

- Battery —> flammable
- Collisions
- Data transfer
- Maintenance

Outlook

Initially: Trajectory —> radial symmetry —> **SfM**

Test Environment

3D model resolution penalty!

Future: Trajectory —> linear —> **SLAM**

(ROI uncertainty)

Greenhouse Environment

References

Li 2023: Automatic Branch–Leaf Segmentation and Leaf Phenotypic Parameter Estimation of Pear Trees Based on Three-Dimensional Point Clouds

Peng 2022: Shape As Points: A Differentiable Poisson Solver

Hu 2022: Metric3D v2: A Versatile Monocular Geometric Foundation Model for Zero-shot Metric Depth and Surface Normal Estimation

Hanocka 2022: Point2Mesh: A Self-Prior for Deformable Meshes

Huang 2018: Robust Watertight Manifold Surface Generation Method for ShapeNet Models

Lindenberg 2018: Pixel-Perfect Structure-from-Motion with Featuremetric Refinement

Wolf 2024: GS2Mesh: Surface Reconstruction from Gaussian Splatting via Novel Stereo Views

Guedon 2024: SuGaR: Surface-Aligned Gaussian Splatting for Efficient 3D Mesh Reconstruction and High-Quality Mesh Rendering

Yu 2024: Gaussian Opacity Fields: Efficient and Compact Surface Reconstruction in Unbounded Scenes

Baar 2022: Non-destructive Leaf Area Index estimation via guided optical imaging for large scale greenhouse environments