Tomato Fruit Evolution and Maturity estimation from RGB Time-lapse Observation

via Modern Structure from Motion and Instance Segmentation

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Research

Motivation

Determine Tomato Fruit Maturity Level

Why?

Passive: Color & Size
Large Scale

Estimate -> Harvest Time & Yield

Primary

Harvest Management

Secondary

Optimise Environment

Maximise **Productivity**/Fruit Yield

PROFITS ↑

Expenditures ↓

→ **Win Capitalism!**

Methodology

HOW? not to do ...

Monitor individual Tomato Fruit Maturity

INPUT

Neural Network,
Machine Learning, etc.

BLACK
BOX Magic

OUTPUT

Maturity

Harvest time

Yield

⋮

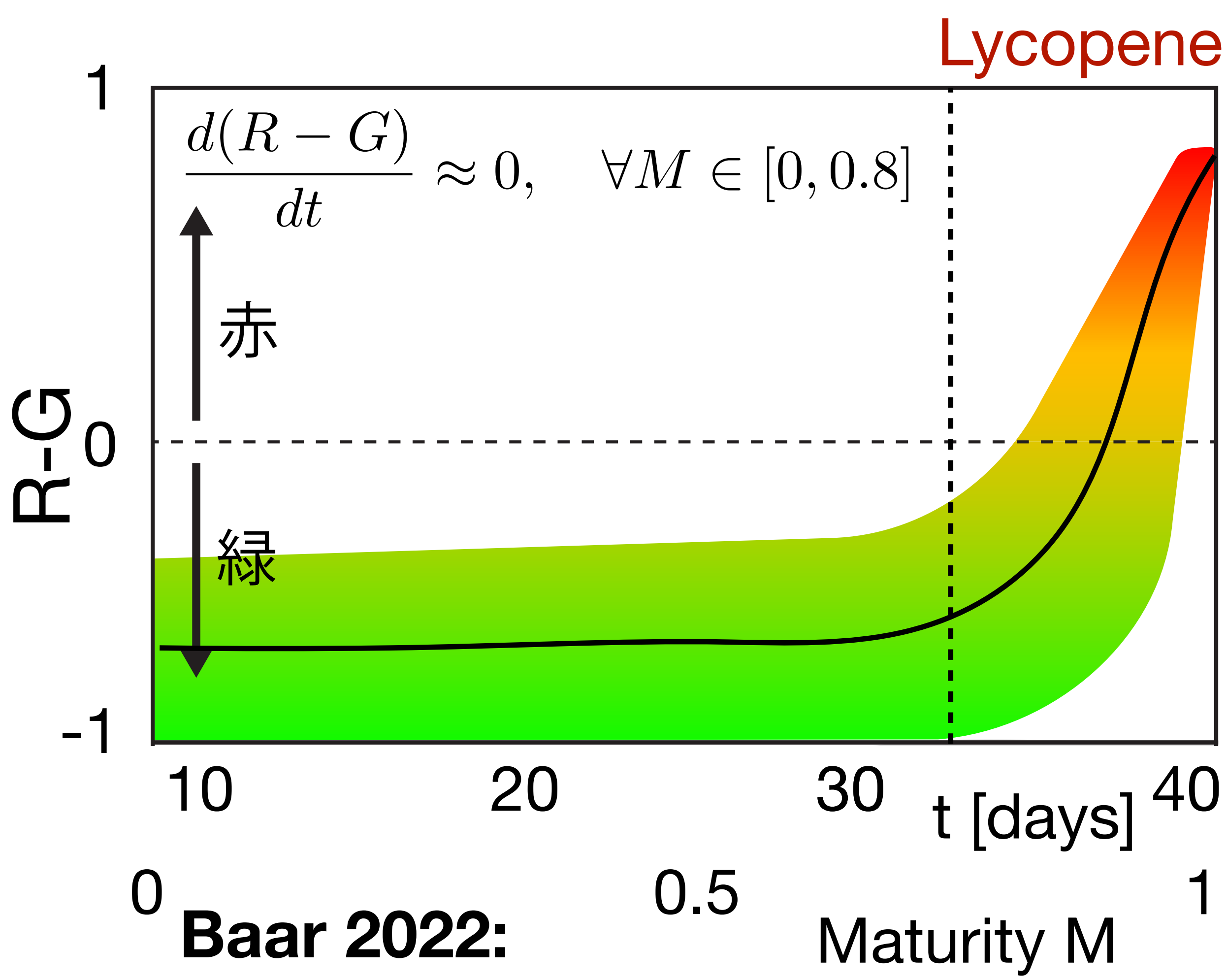
- High Attention (WOW!)
- Low Effort

- Low Reliability
- Low Reproducibility
- No Comprehensibility

Motivation

Color vs. Diameter

Monitor individual Tomato Fruit Maturity



Baar 2022:

Color variability:

- ✓ Calibrated by B
- ✓ R-B as maturity indicator
- R-B flat for first 80% of maturity
- Not geometrically uniform

Brightness variability:

- Dominant in early and late stage
- Biased by environment

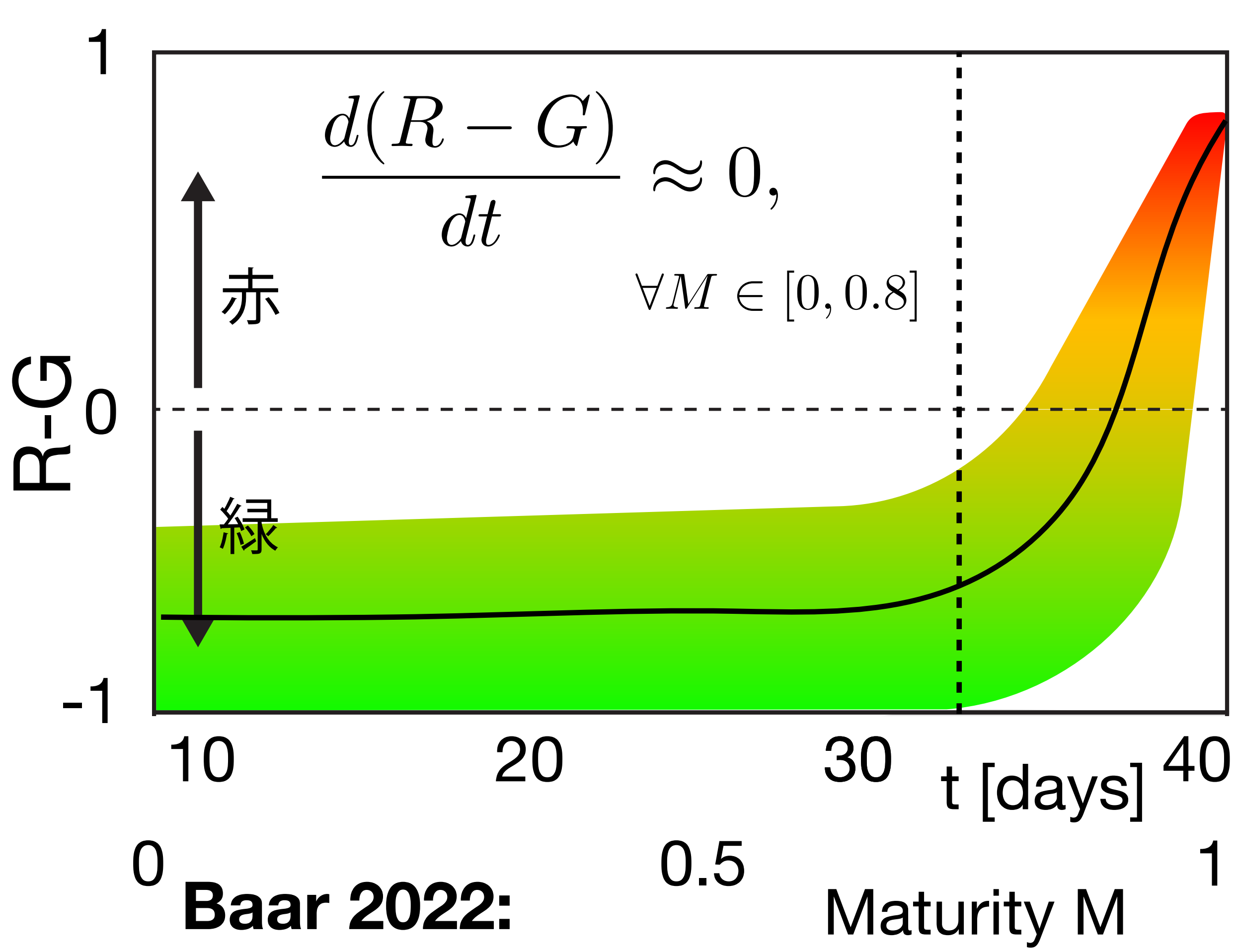
Maturity evaluation by color:

Very difficult!
Unreliable!

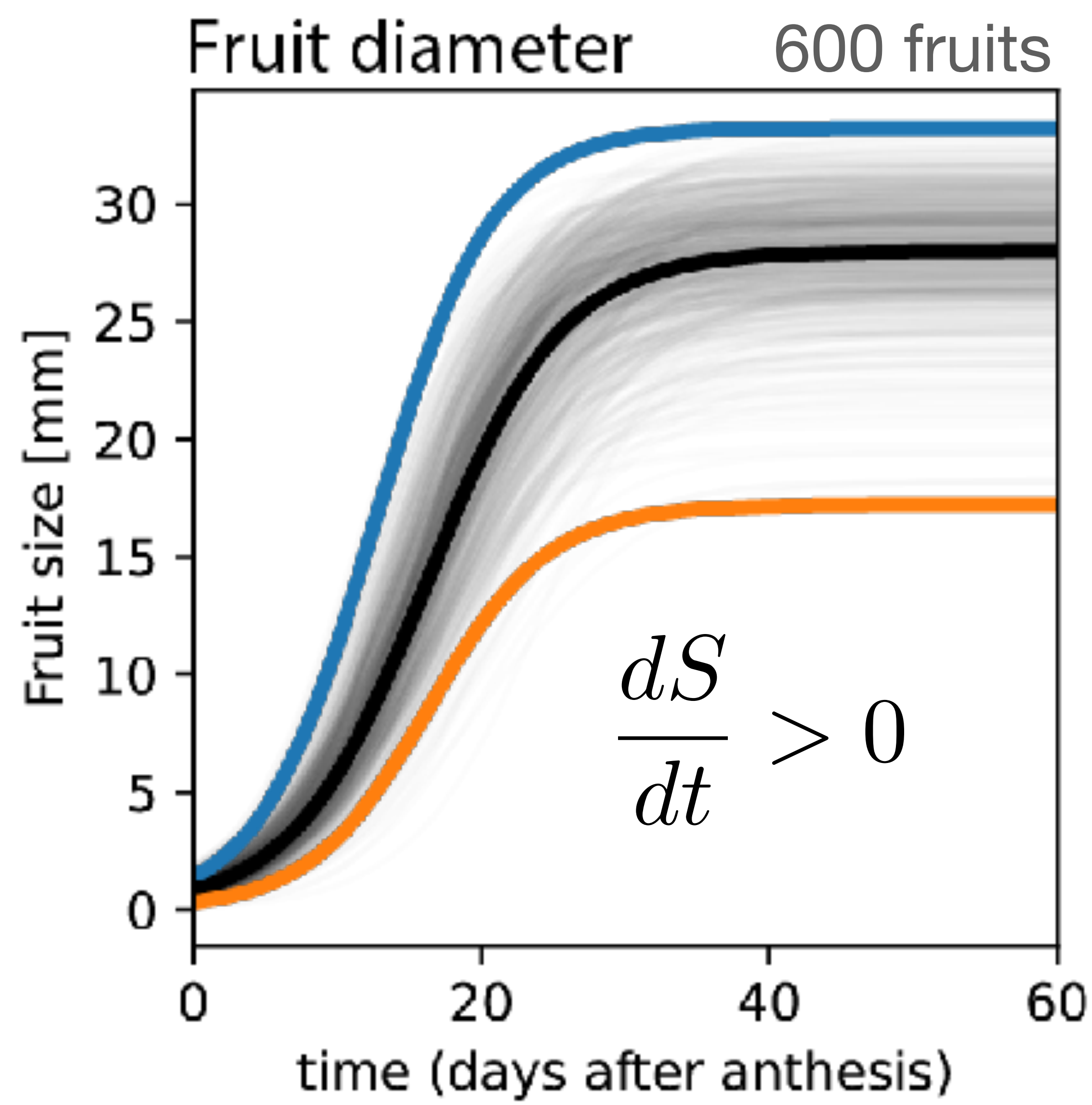
Motivation

Color vs. Diameter

Monitor individual Tomato Fruit Maturity



Baar 2022:



Motivation

Color vs. Diameter

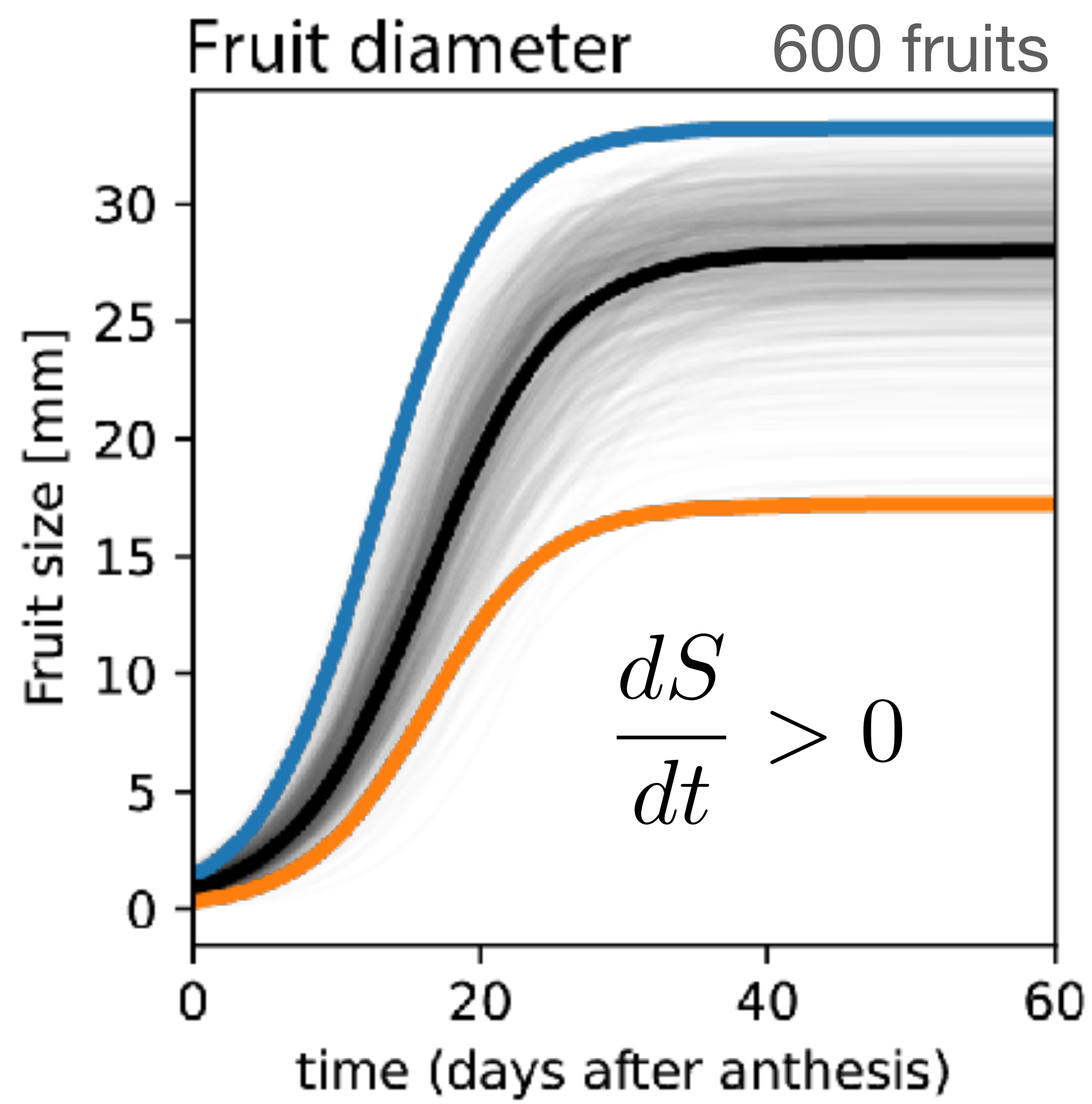
Monitor individual Tomato Fruit Maturity

Fruit size:

- ✓ Well defined for all times
- - Not from single image
- - Req. Reference
- - Depends on shape
- - Depends on species

How to?

Baar 2024



Methodology

Workflow

Not End to End, but understandable

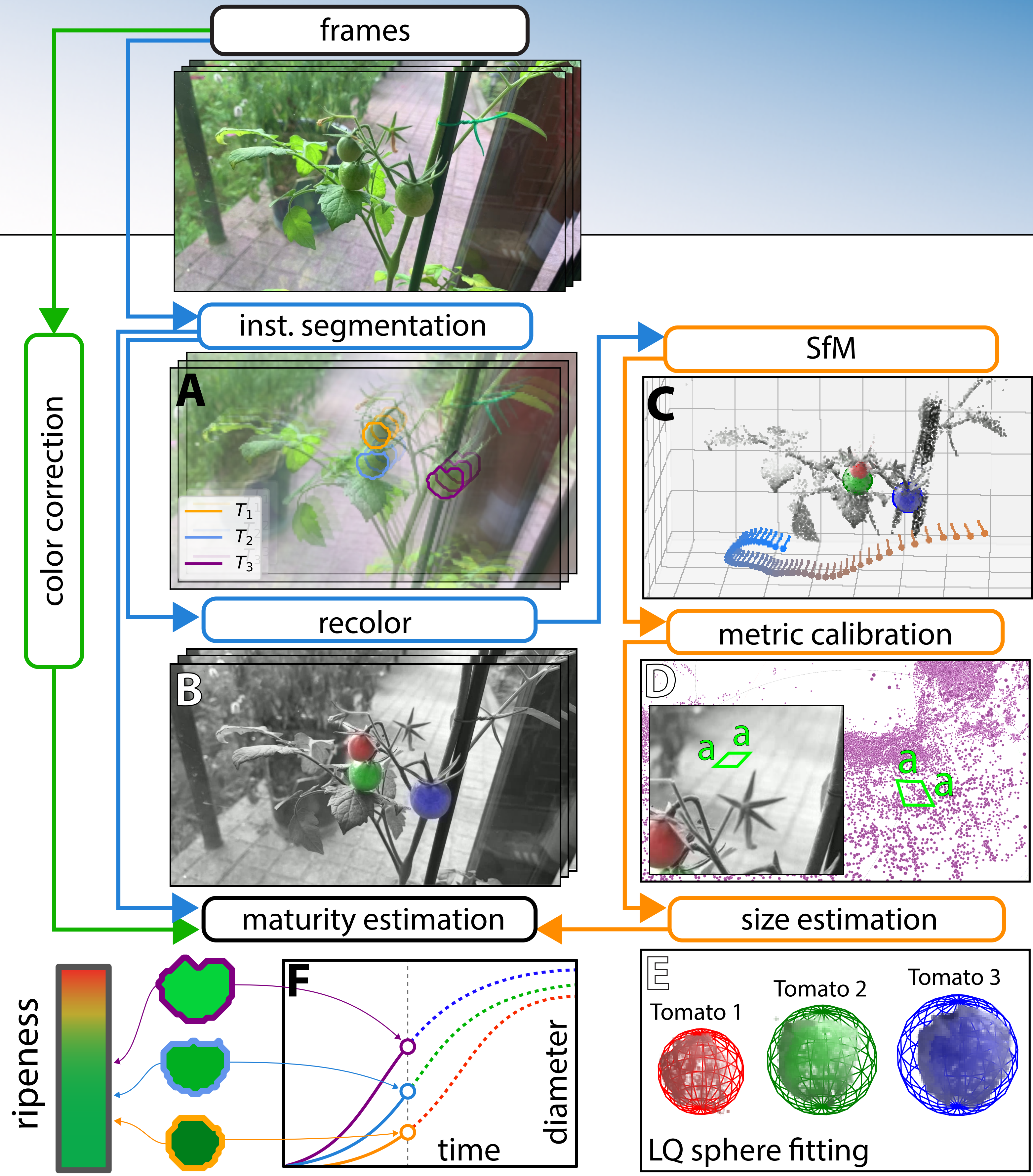
- Requires ~ 20 frames/Obs
- Returns Fruit diameters

Consist of:

- Computer Vision

- 3D reconstrucion

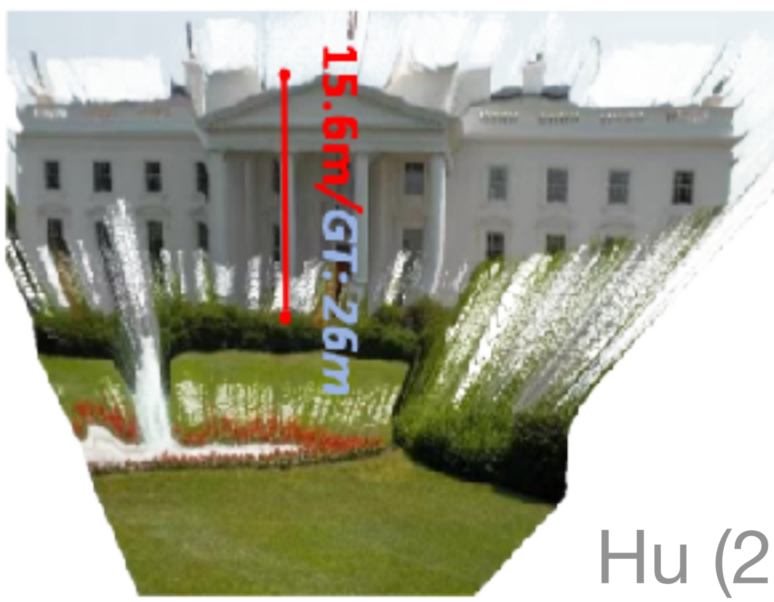
- Math. Modelling



Observational Requirements

Single vs. Multi View

Single View



Hu (2024)

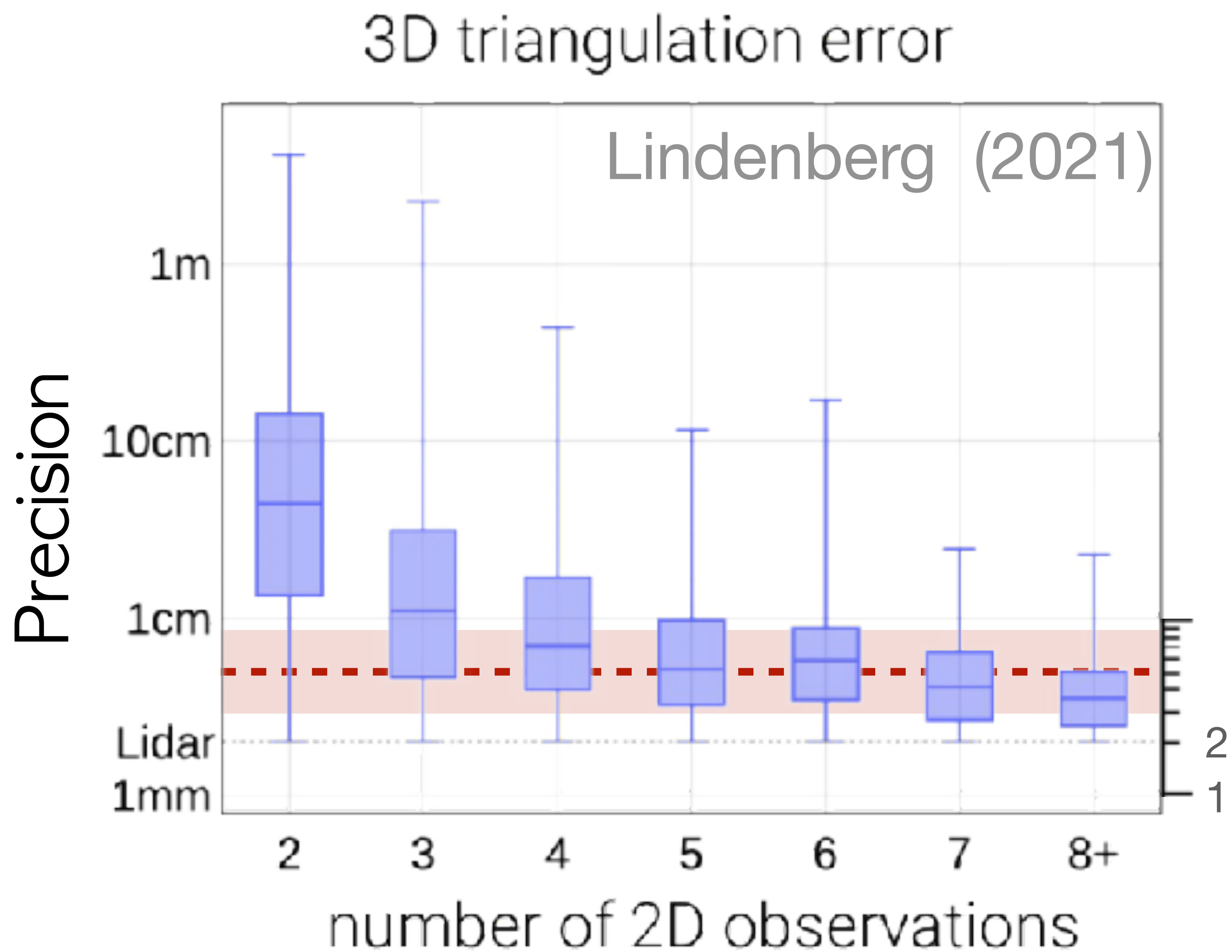
Metric3D v2: A Versatile **Monocular Geometric** Foundation Model for Zero-shot Metric Depth and Surface Normal Estimation

Yin et al. 2023

High variance

Low confidence

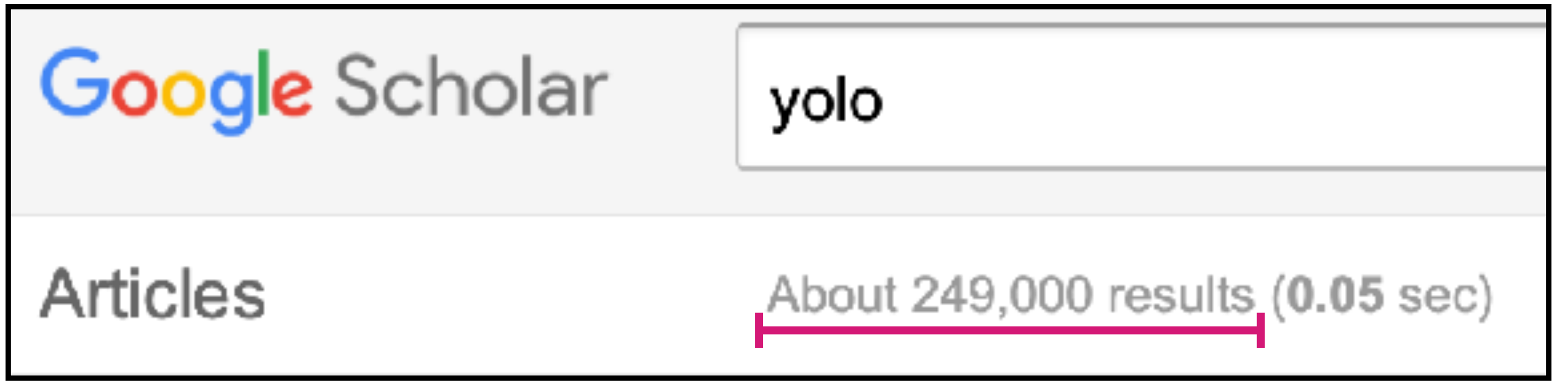
Multi View

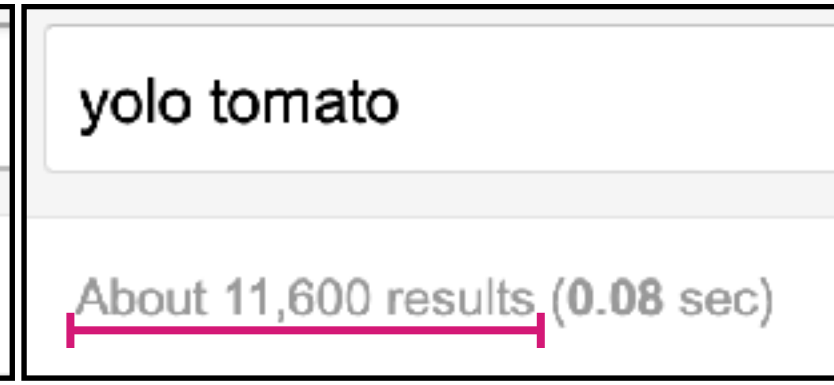


Need 8+ frames !

Related Research

What about YOLO?





2D Image

Segmentation

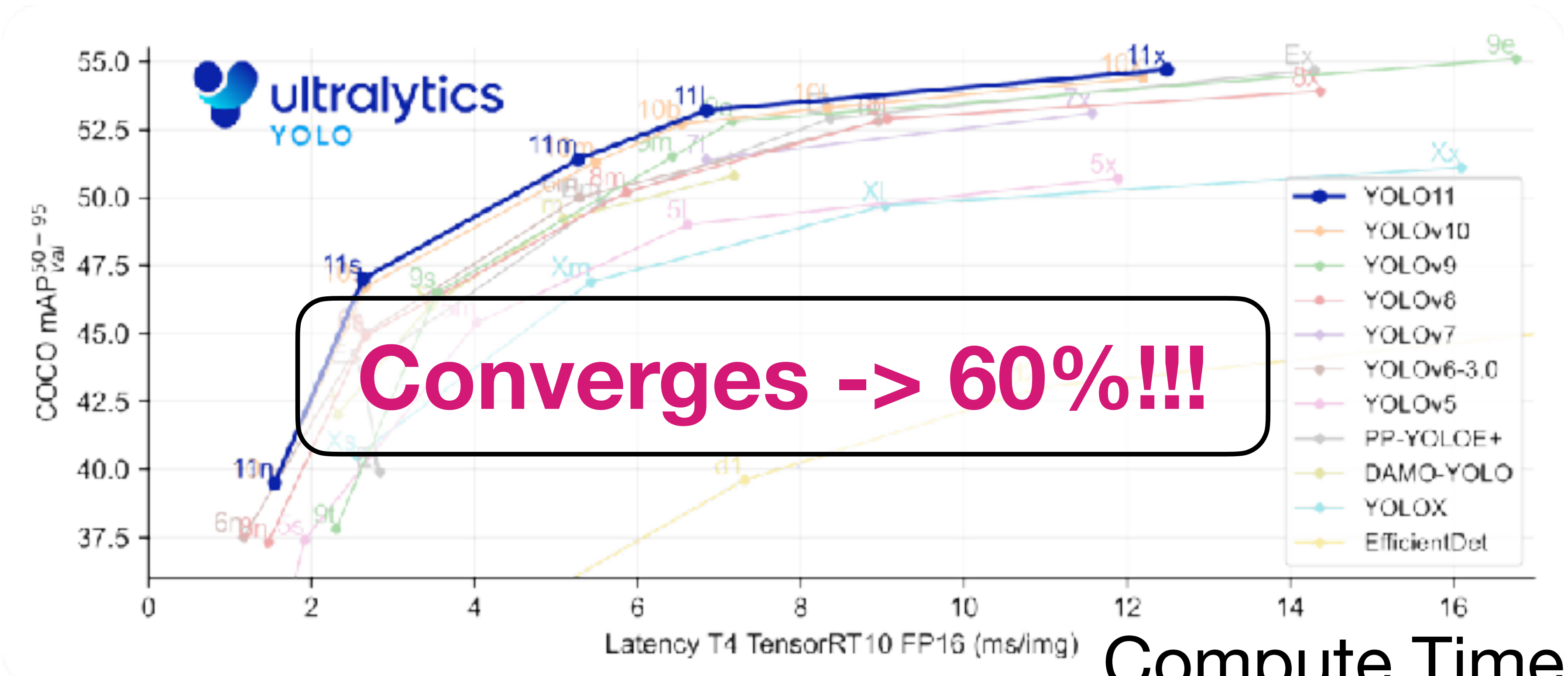
Detection

Ripeness est.

Always Volatile!!

Low Reliability

Precision



Compute Time

- Not Interesting
- **Over-utilised**

source: ultralytics.com

Tomato Segmentation

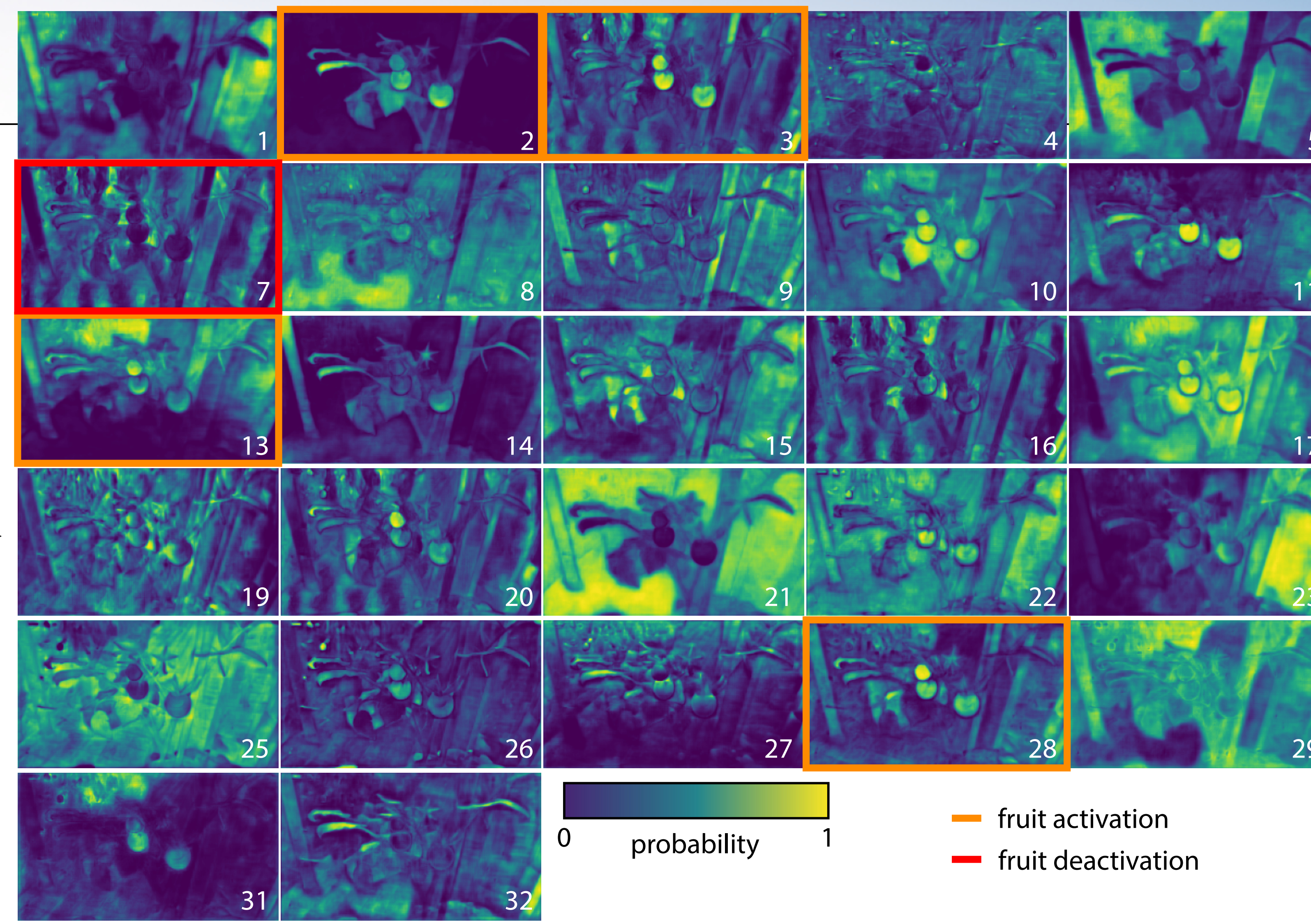
pre-trained YOLO?

YoloV9-seg

Recomb. Activations

$$P_{tomato}^{u \times v} = \sum_{n}^{N} w(n) p(g)^{u \times v}$$

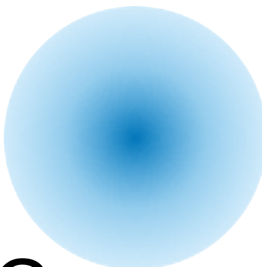
Next Slide



- Contains no Tomatoes, but apples and oranges (2,3)
- Recombining Pre-trained features
- No retraining!

3D Reconstruction

Methodology



Grey+Gauss

1 **Features**
hloc-super glue

2 **SfM model**
Gaussian-Splatting

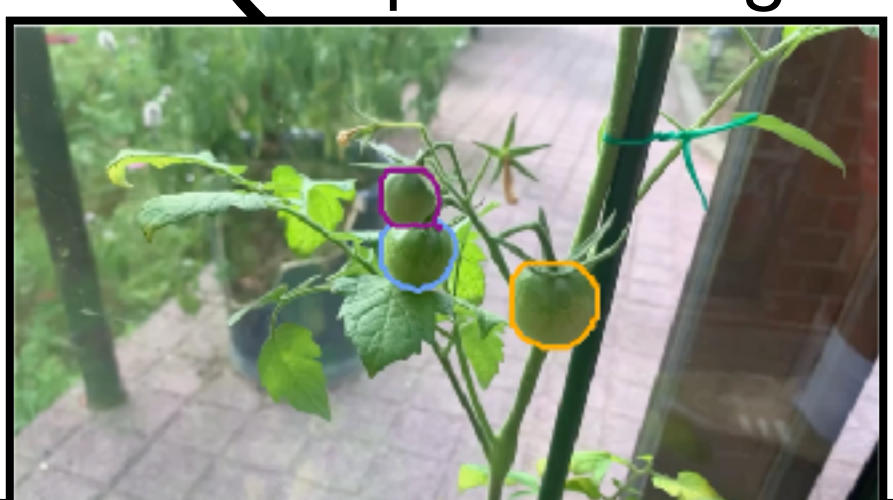
3 **Metric Calibration**
Reference Sphere

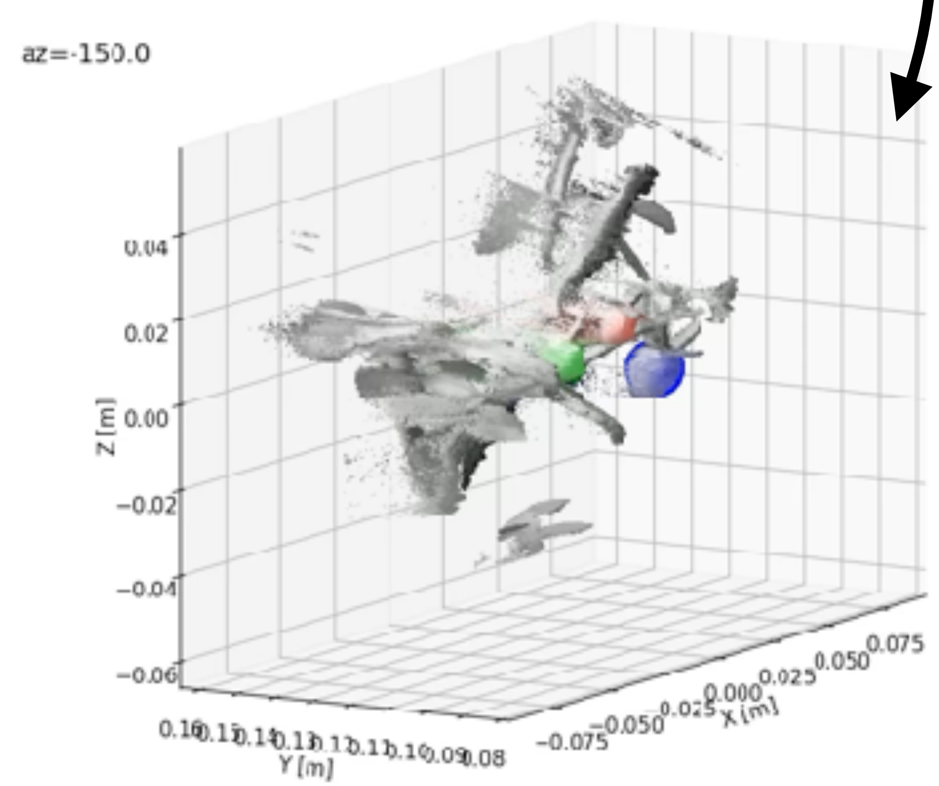
Tasks:
- feature extraction
- feature matching
- bundle adjustment

Results:
- **3D Splats**
- **Camera parameters**

Intrinsic
Extrinsic
Parameters

Imperfect segments





Metric Calibration

Calibration Methods

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

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

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

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

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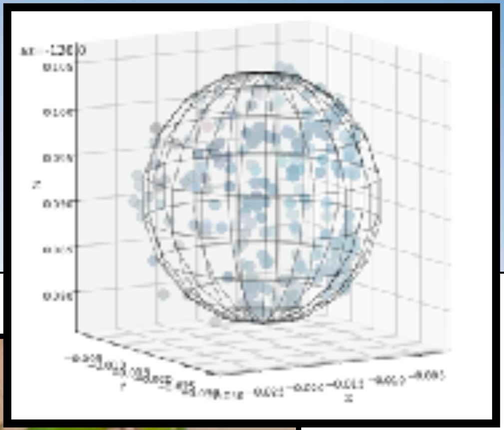
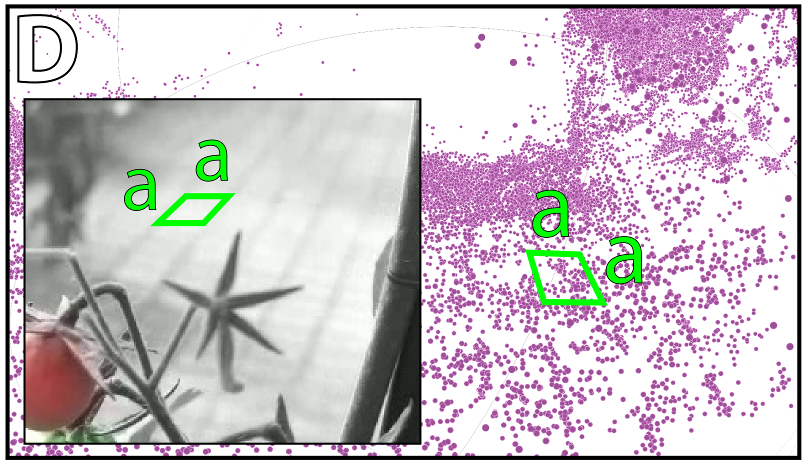
Calibrator



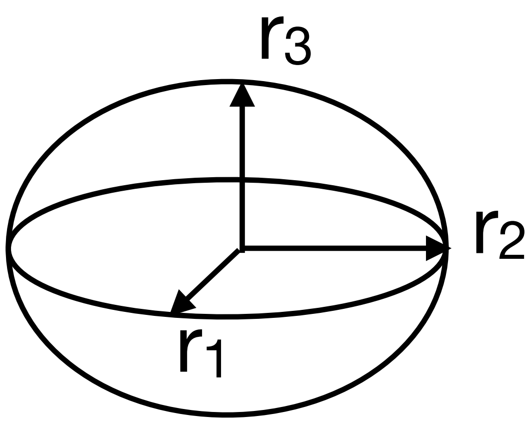
A - ref. Object



B - ref. Pattern

Metric Calibration

Complete vs. incomplete scenes



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

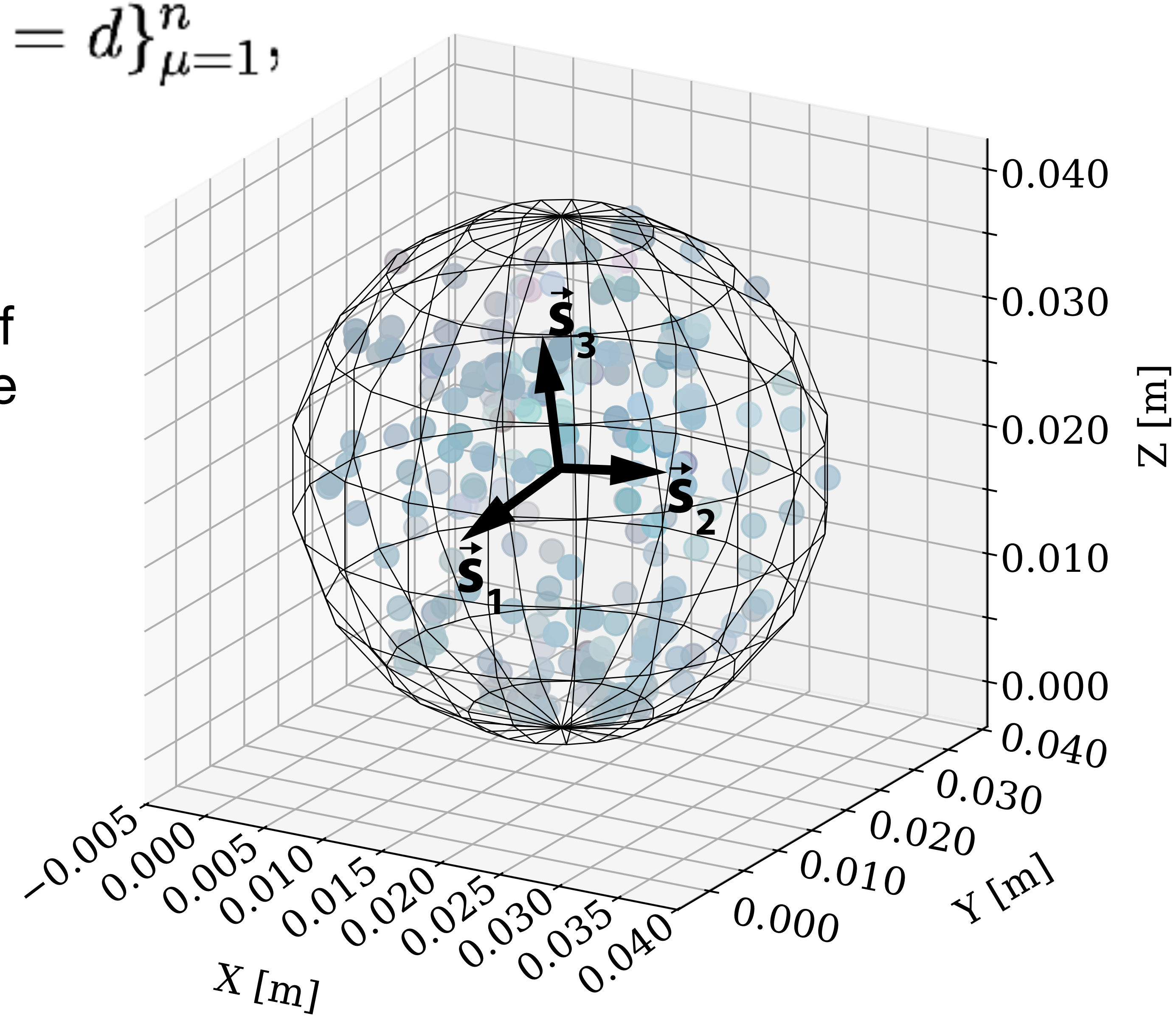
Eigenvectors of S give the directions of the principal axes of the ellipsoid, while its eigenvalues $(\lambda_i)^d$ are related to the lengths (r_i) of its principal (semi-)axes by

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

Table 2: **Metric**

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

Calibrator (ref. Object)



Why ellipsoid?

Metric Calibration

Complete vs. incomplete scenes

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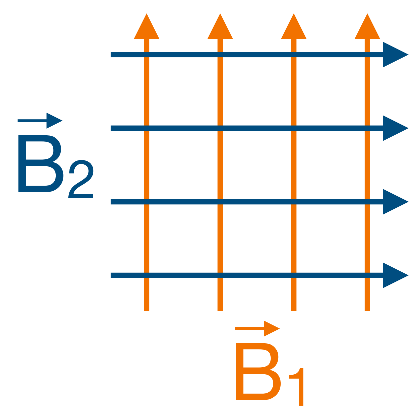
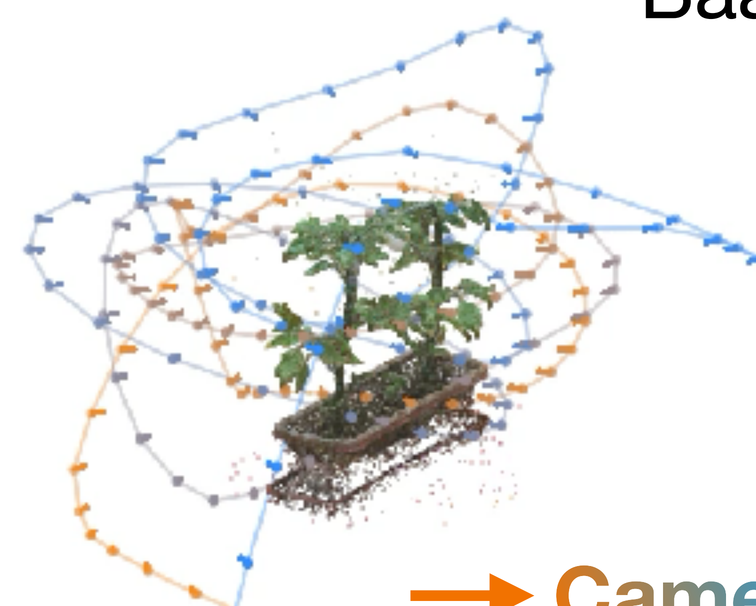
Complete Scene Coverage

g is homogenous
g -> scalar

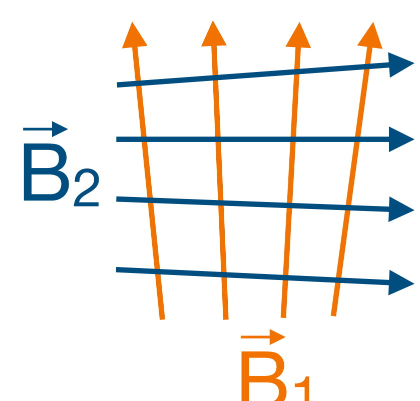


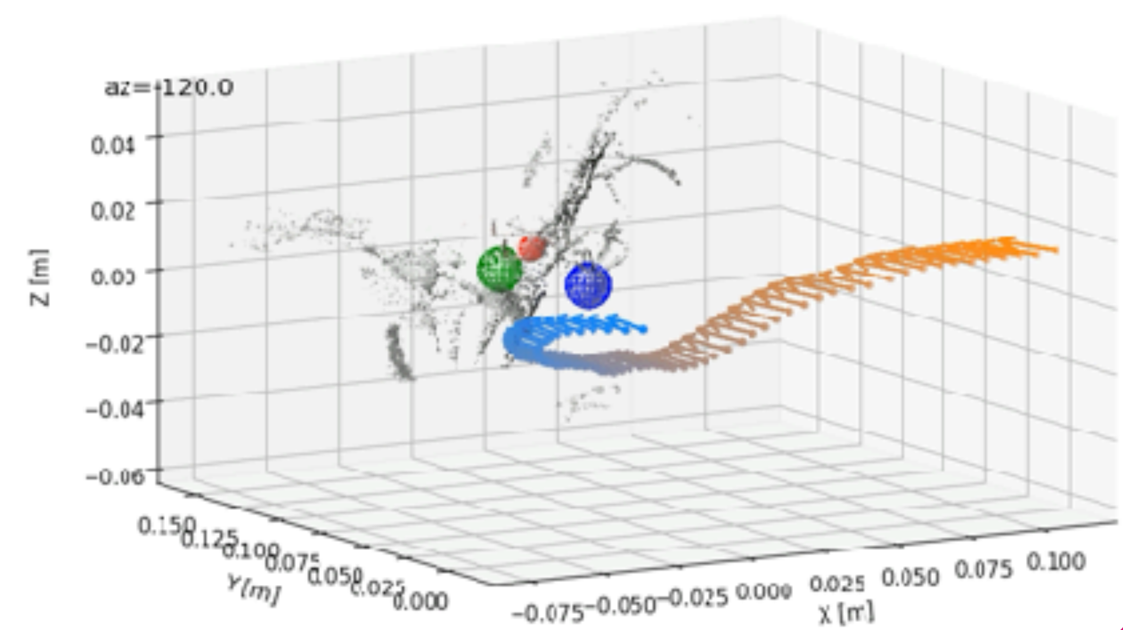


Camera
t ∈[0s,…,2s]

Incomplete Scene Coverage

Biased/ one sided
Conical distortions of g



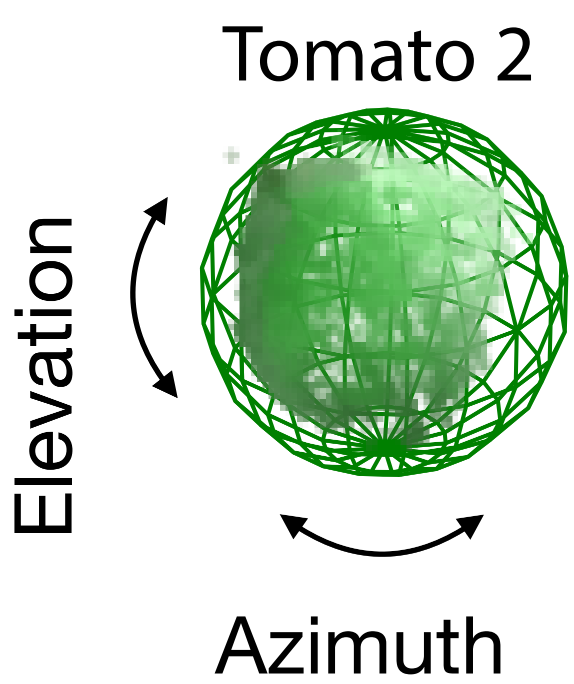


Size Estimation

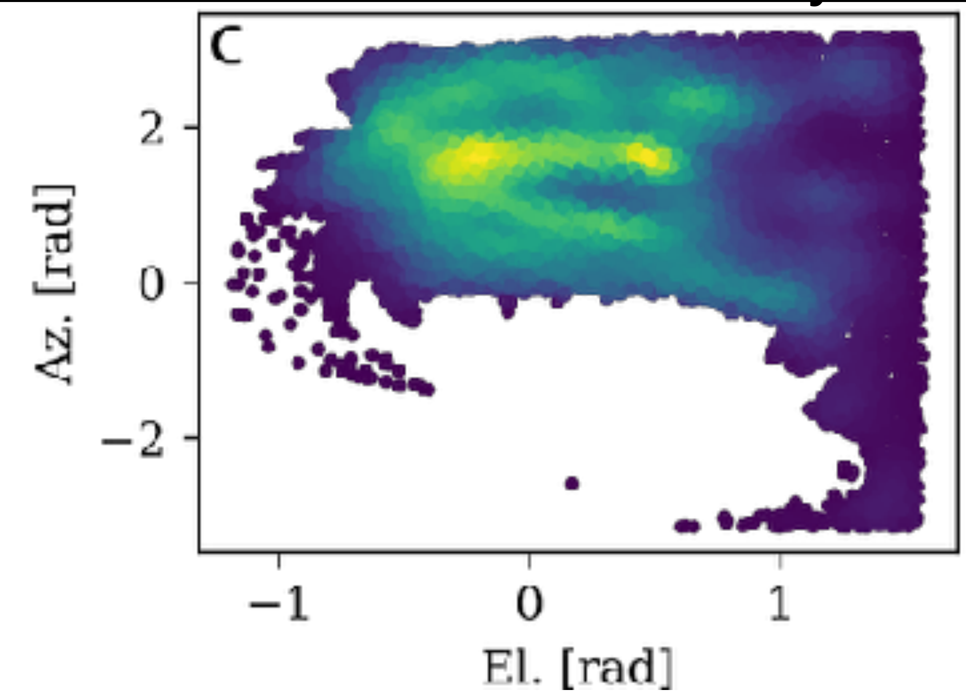
Fruit size from 3d Point Cloud

Same as for calibration

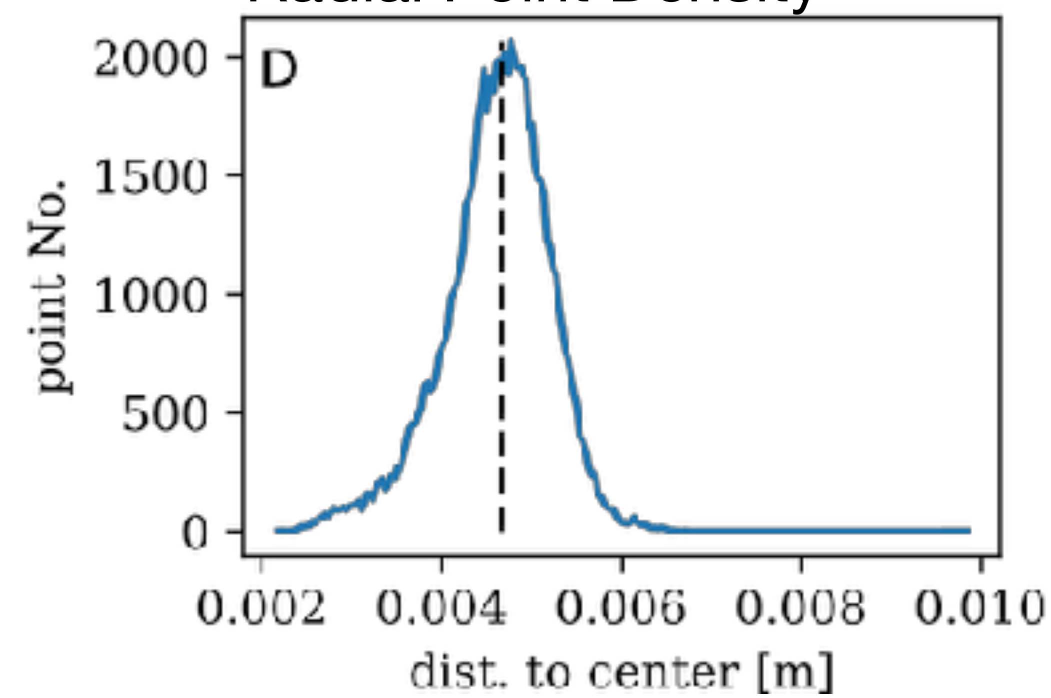
$$(\mathrm{P}) : \begin{cases} \{\mathbf{x}_\mu^\top \mathbf{S} \mathbf{x}_\mu = d\}_{\mu=1}^{n}, \\ \mathbf{S} \succeq 0, \end{cases}$$



Lateral Point Density



Radial Point Density

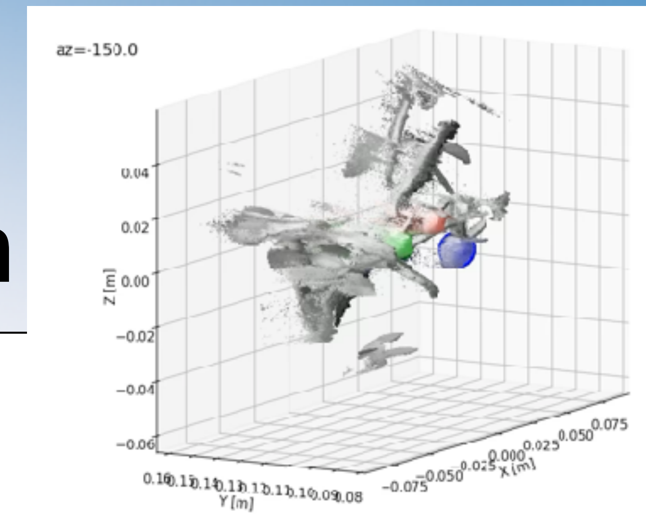


$d_{1,2,3}$ = D, Diameter

- For Spherical Fruit Genotype
- D form statistical distance to centre

Results

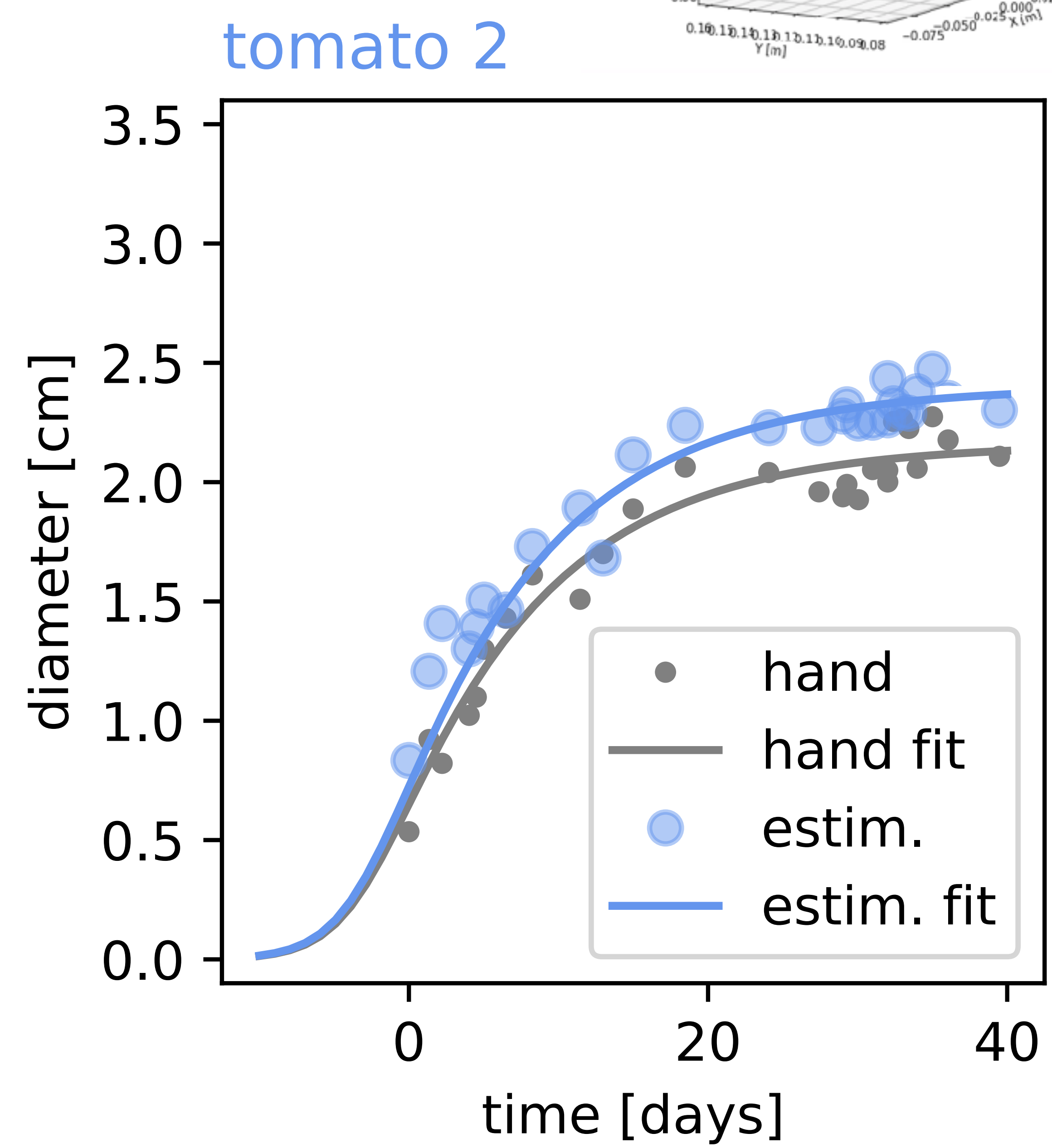
Maturity Estimation - Richard’s Function



Describes Cell Growth
Generalised Sigmoid

$$f_R(x) = D_{tomato}(x) = a + \frac{A - a}{(c + be^{-d(x - x_0)})^{1/z}}$$

Only keep b and d



Derive Normalised Fruit Maturity

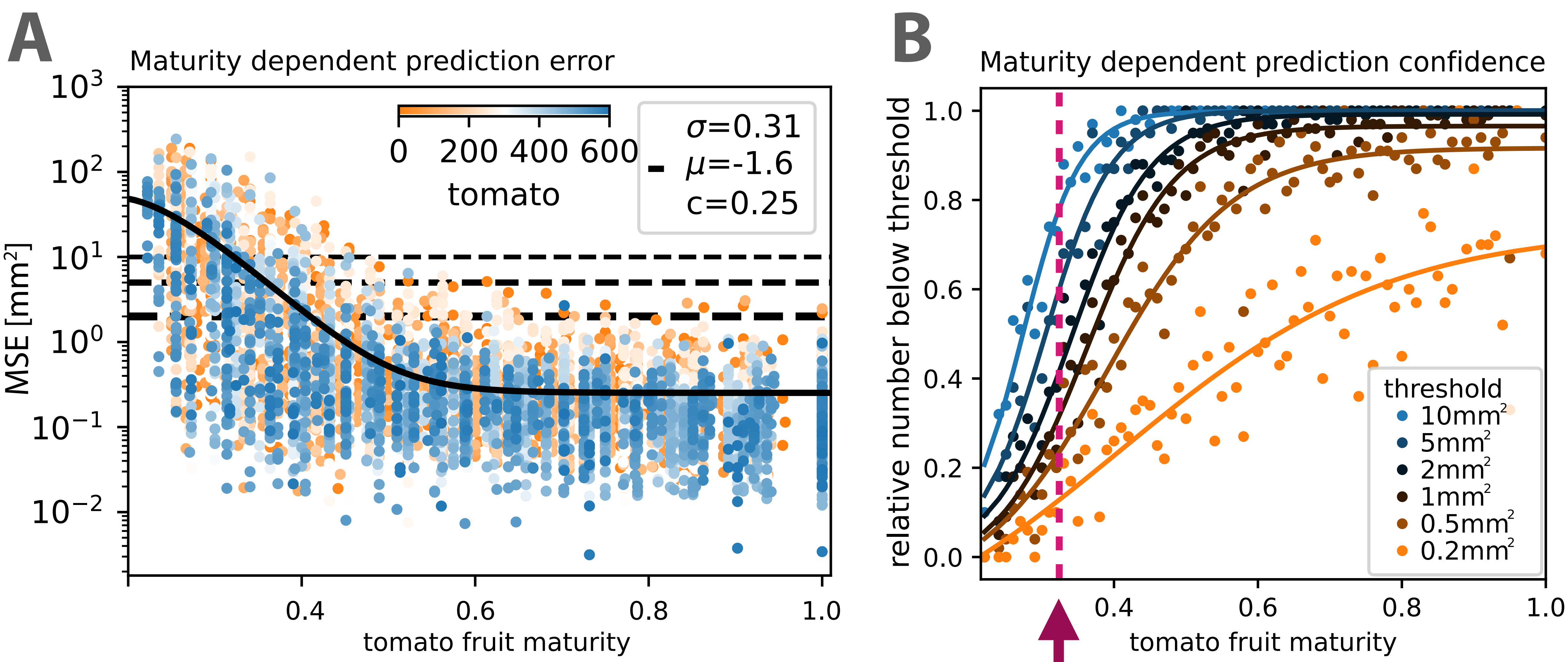
$$M_f(D_h = 0.95A) = \frac{x}{\frac{1}{bd} ln(1.05^d - 1) + x_0}$$

A: final diameter, d: growth rate,
x: time, x0: start of obs.

0 → Maturity → 1

Discussion

Maturity Estimation



6000 observations of 600 fruits

- high confidence above M=0.3

Conclusions

What we have learned

End-to-End not possible

- **maturity from color not possible**
- no environmental awareness
- Features a invariant -> scale is not

Precise 3D structures from videos

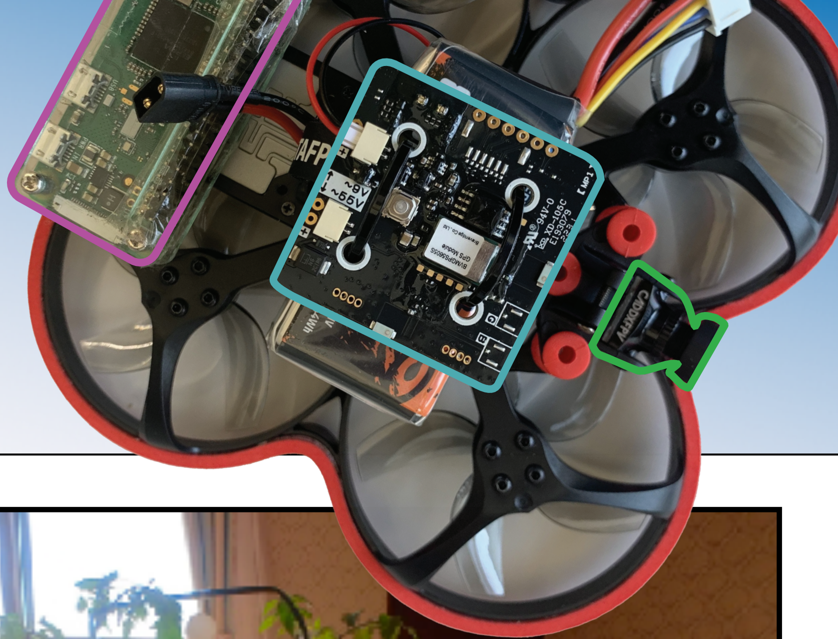
- Req. **low** brightness contrast
  - Avoid shadows and highligths
- **high** colour contrast
- Proper white balance

Outlook

Test Environment ⟶ Greenhouse Environment
Baar 2022, Baar 2024

Outlook

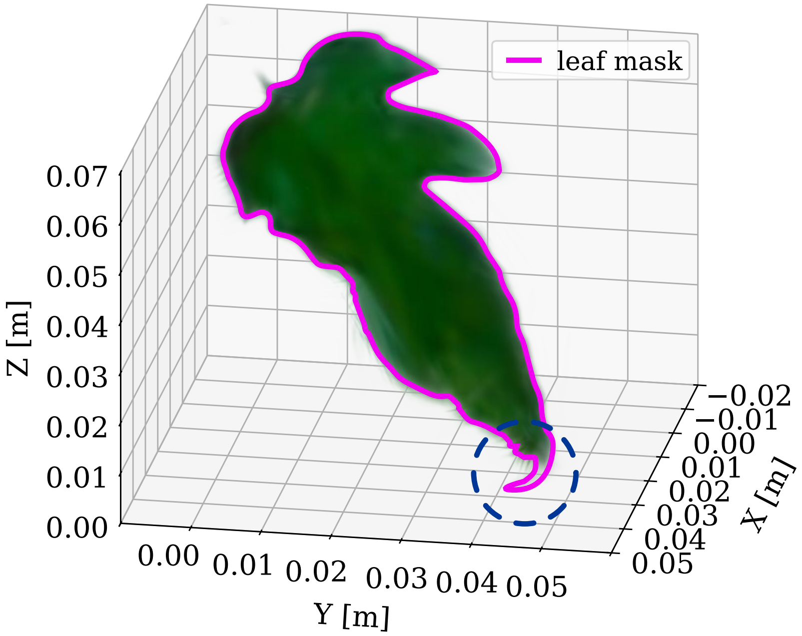
Plant Phenotyping



Leafs GCCE 2024

2024/10/29

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



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

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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**

Baar 2024: **A logistic model for precise tomato fruit-growth prediction based on diameter-time evolution**