Contour Detection in Multi-Angle Time-Lapse Images of Growing Plants

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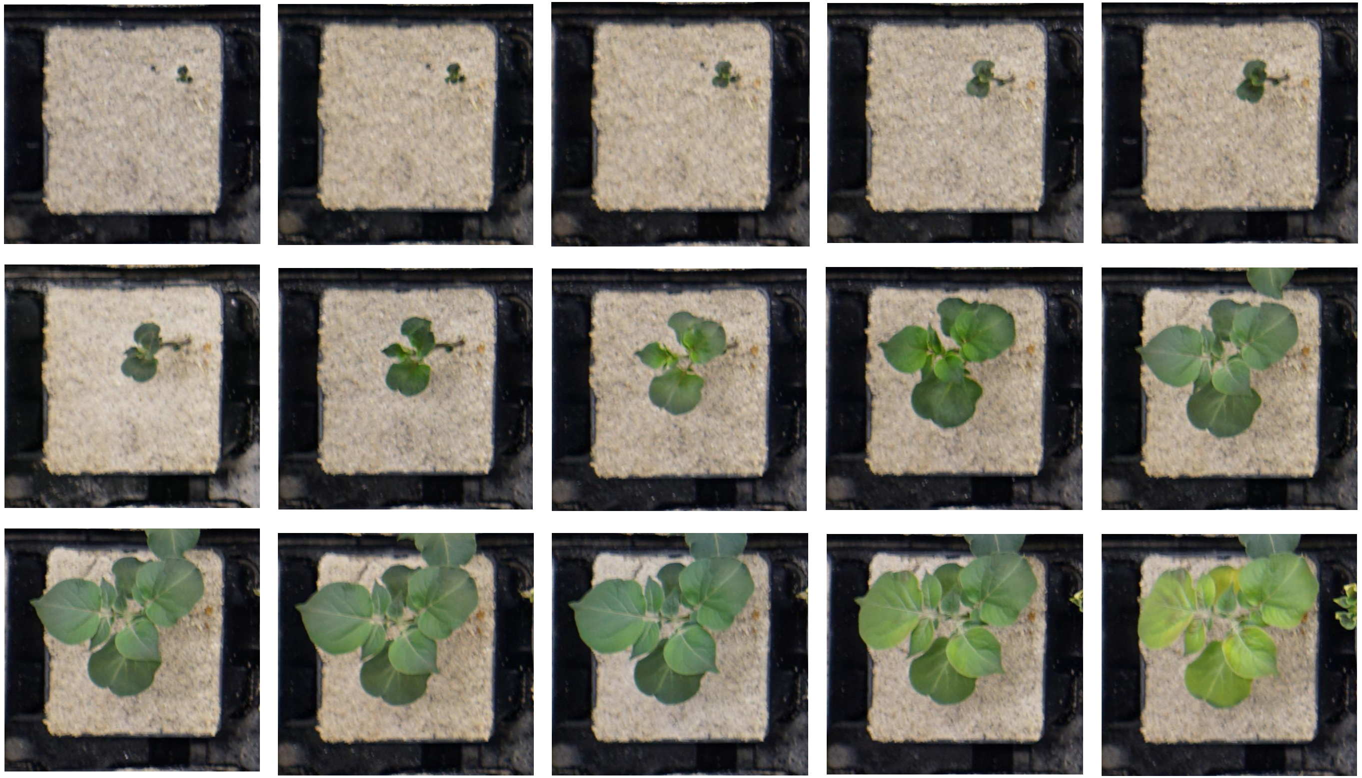
TU Delft

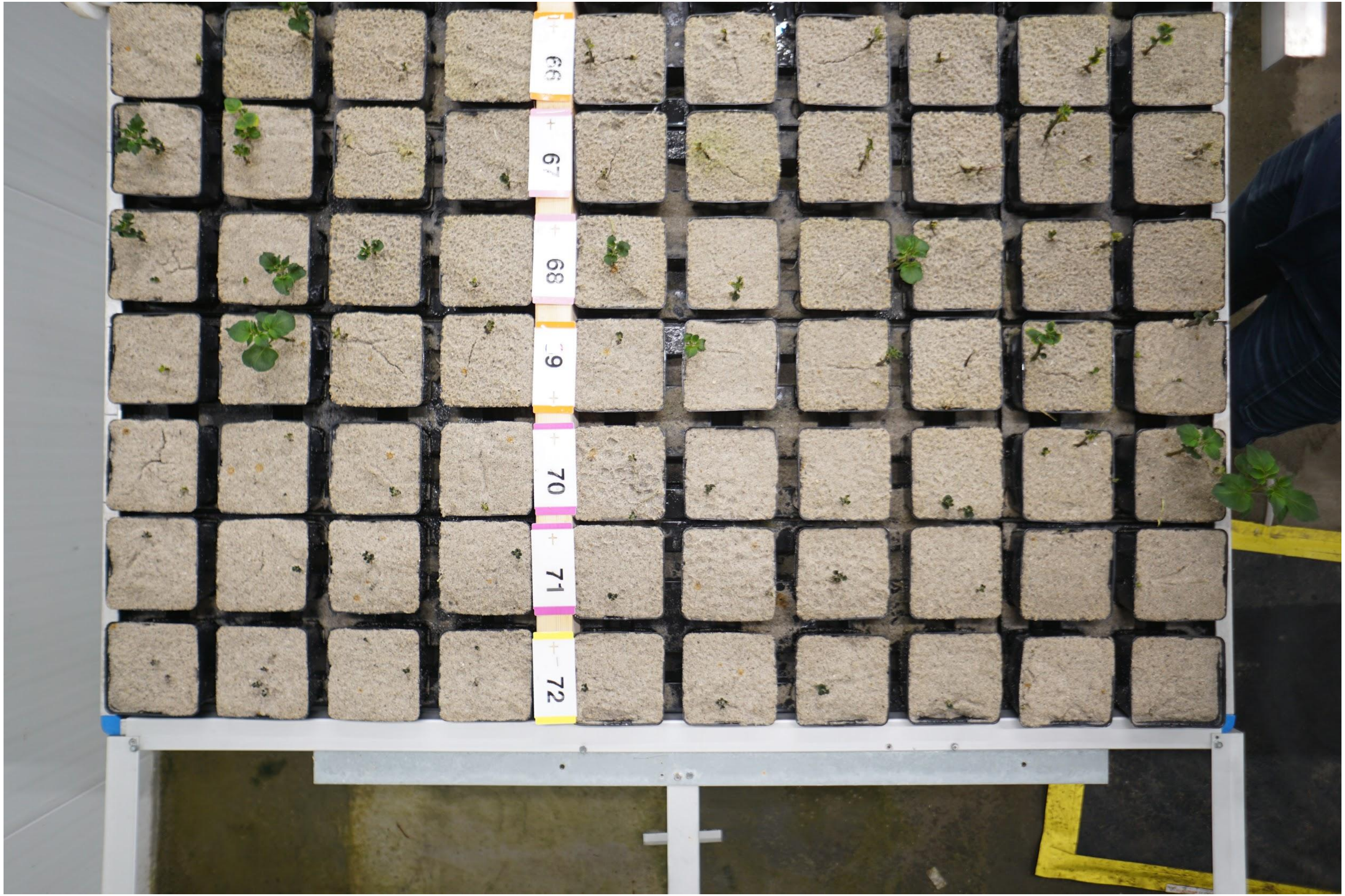
Quantifying growth

- Six potato varieties
- 2 Climate rooms
- Dry and wet sections

HZPC
keeps you growing

Problem

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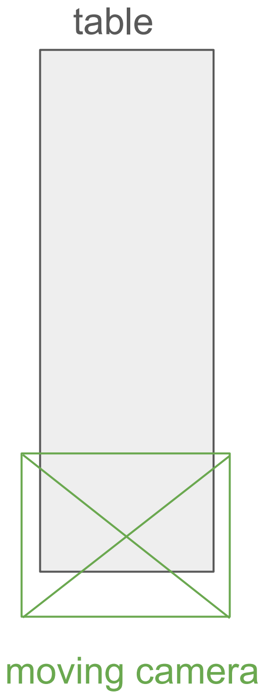
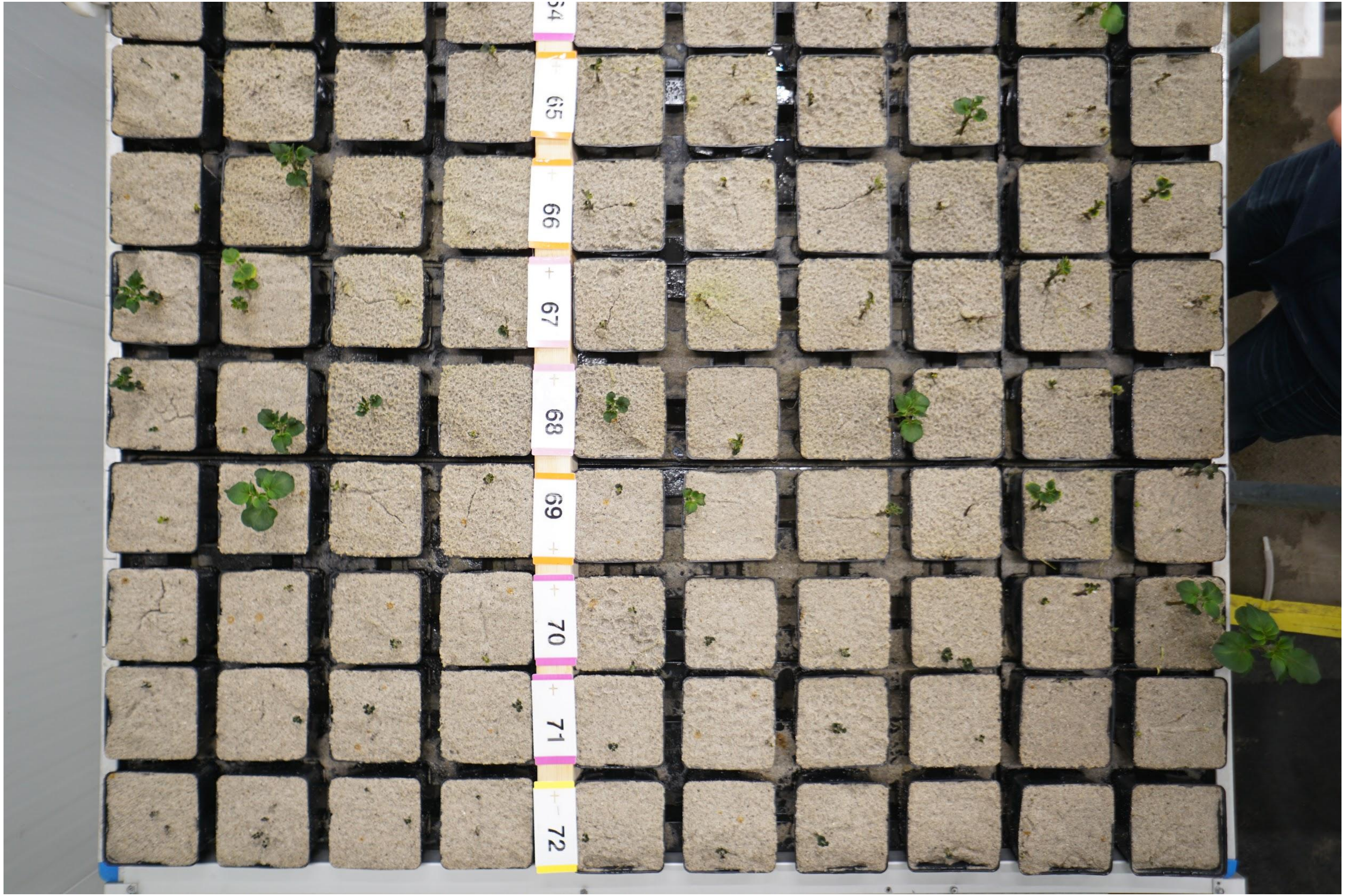


table
moving camera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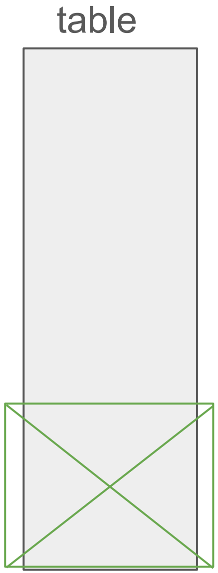
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63
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66
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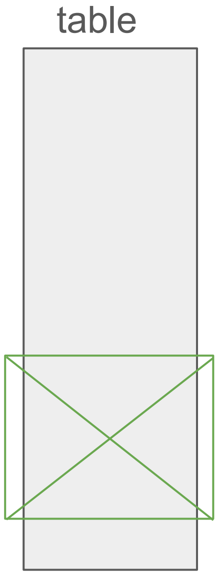


table

Overview

Contour detection

To detect the outline of the plant

3D Contour Reconstruction

Using a pinhole camera model

Double Snakes

Combination of previous problems

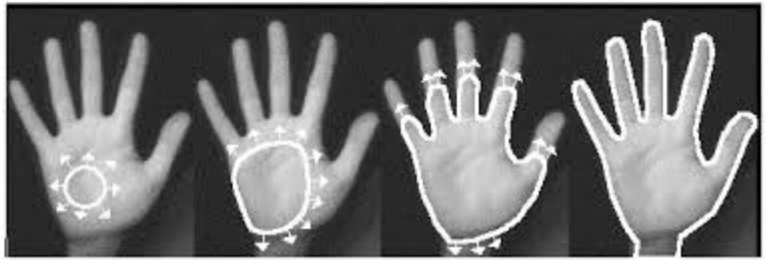
Conclusion

Conclusion and recommendations

Traditional Snakes

Contour detection

- Active contours to detect outline in image



Traditional Snakes

- Energy functional of a traditional snake parameterized by $\mathbf{q}(s) = [u(s), v(s)]$

$$E^*_{\text{snake}} = \int_0^1 E_{\text{snake}}(\mathbf{q}(s))\,\mathrm{d}s$$
$$= \int_0^1 E_{\text{int}}(\mathbf{q}(s)) + E_{\text{ext}}(\mathbf{q}(s))\,\mathrm{d}s$$

- α and β control parameters for amount of stretch and curvature

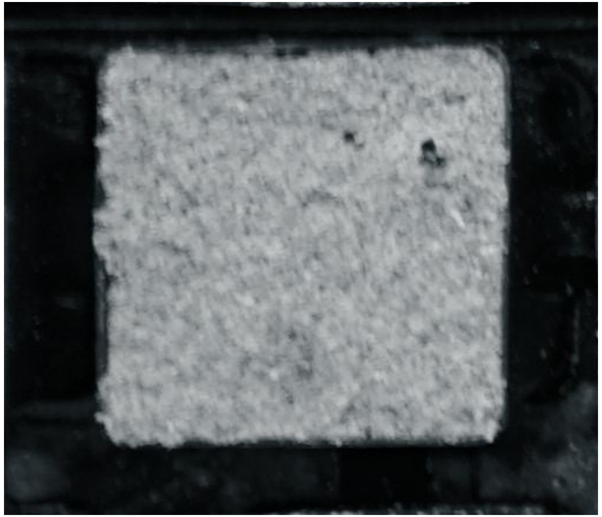
$$E[\mathbf{q}] = \int_0^1 \frac{1}{2}\left(\alpha \left\|\mathbf{q}'(s)\right\|^2 + \beta \left\|\mathbf{q}''(s)\right\|^2\right) + E_{\text{ext}}(\mathbf{q}(s))\,\mathrm{d}s$$

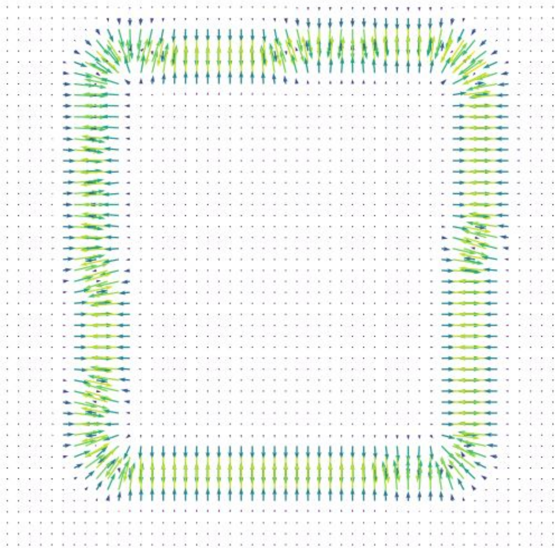
- Assume local minimum of E in $\mathbf{q}$ to derive the Euler-Lagrange equation

$$\alpha\mathbf{q}'' - \beta\mathbf{q}'''' - \nabla E_{\text{ext}}(\mathbf{q}) = 0$$

Traditional Snakes

- Typical external energy $E_{\text{ext}}(\mathbf{q}) = -\left|\nabla I(\mathbf{q})\right|^2$ which points towards regions of interest in image I





Gradient Vector Flow

- New external force field $\mathbf{w}(u,v) = [\phi(u,v), \psi(u,v)]$ which minimizes the functional

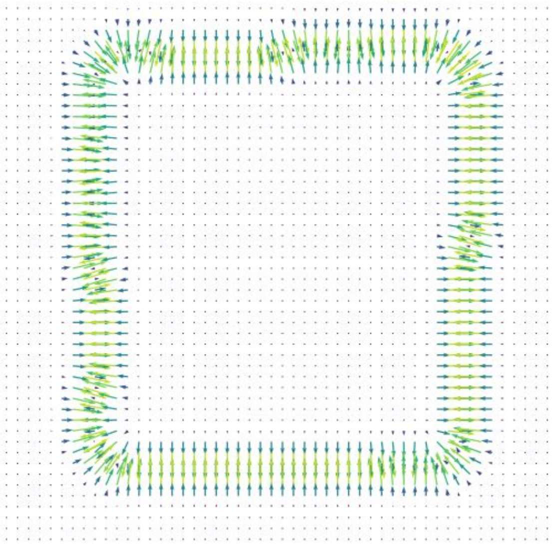
$$\mathcal{E}[\mathbf{w}] = \iint \mu \left(\phi_u^2 + \phi_v^2 + \psi_u^2 + \psi_v^2\right) + |\nabla f|^2 |\mathbf{w} - \nabla f|^2 \, \mathrm{d}u \, \mathrm{d}v$$

μ smoothing term and edge map f derived from image

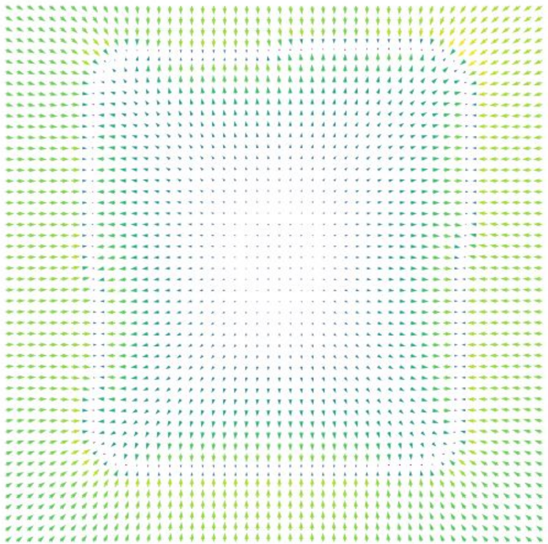
- GVF Snake

$$\alpha \mathbf{q}'' - \beta \mathbf{q}'''' + \mathbf{w} = 0$$

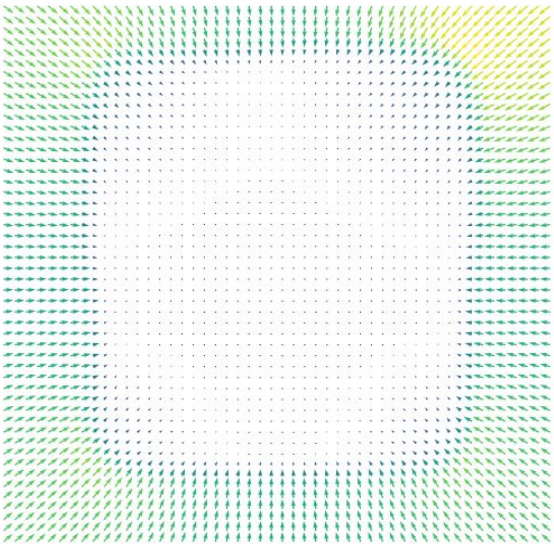
Gradient Vector Flow



μ=0



μ=1e-3



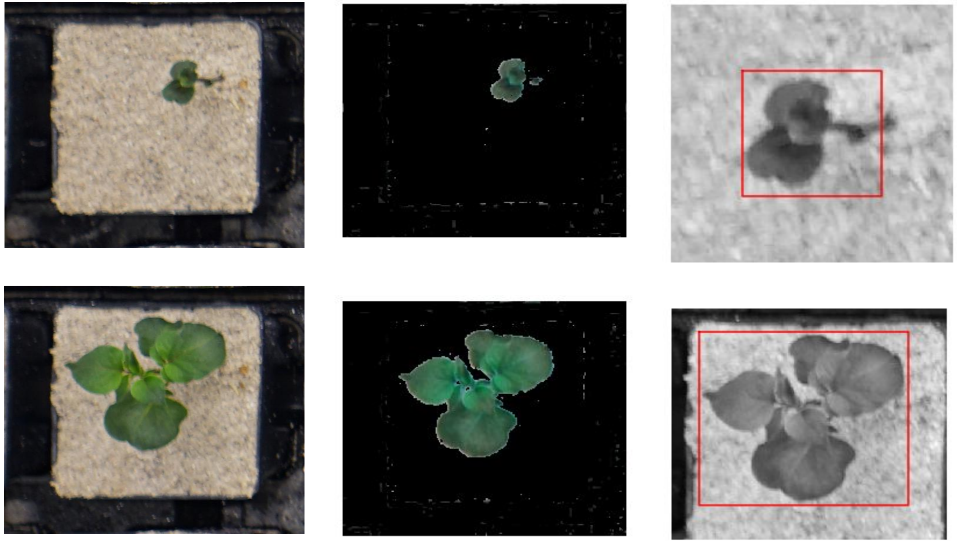
μ=0.1

GVF-Snakes

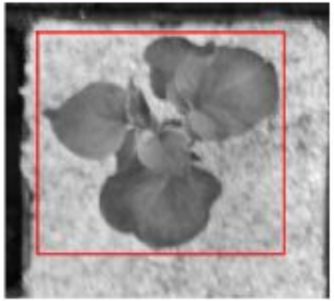
- Solve for $\frac{\partial \mathbf{q}}{\partial t} = \alpha \frac{\partial^2 \mathbf{q}}{\partial s^2} - \beta \frac{\partial^4 \mathbf{q}}{\partial s^4} + \mathbf{w}(\mathbf{q})$

  with time-integration method

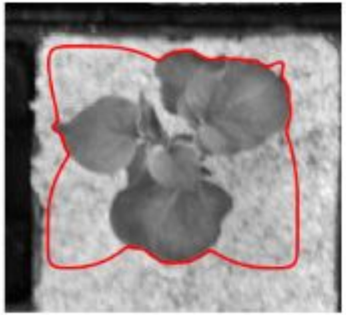
- Initial contour



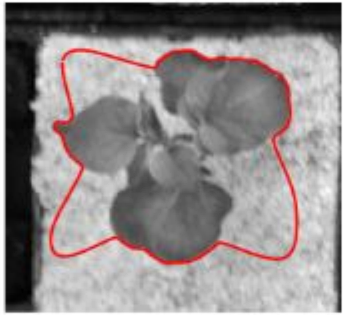
Results



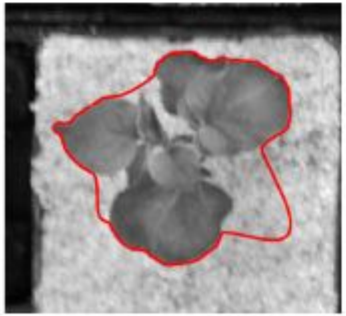
(a) $t = 0$



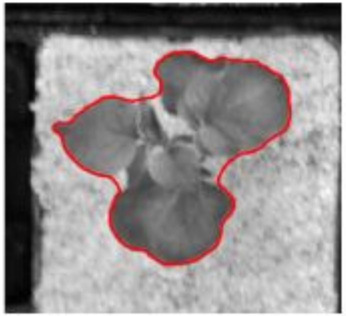
(b) $t = 1$



(c) $t = 5$



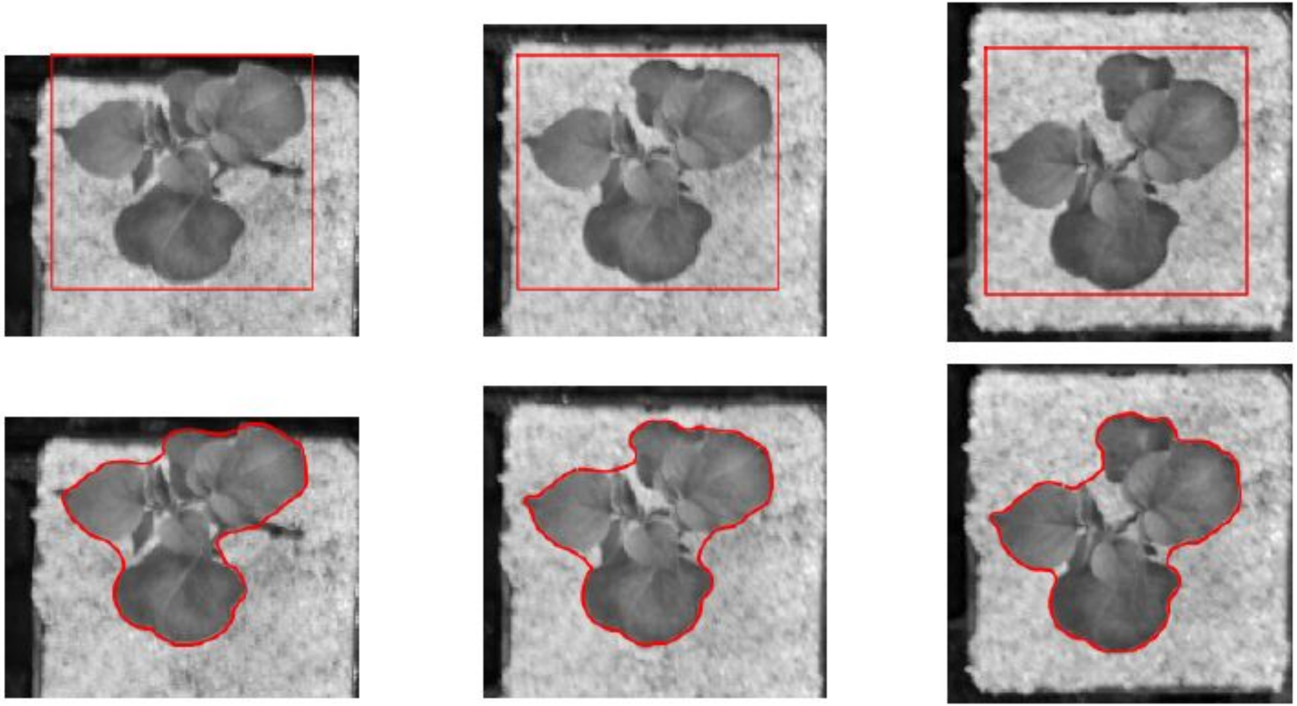
(d) $t = 10$



(e) $t = 50$

Results

Contour detection

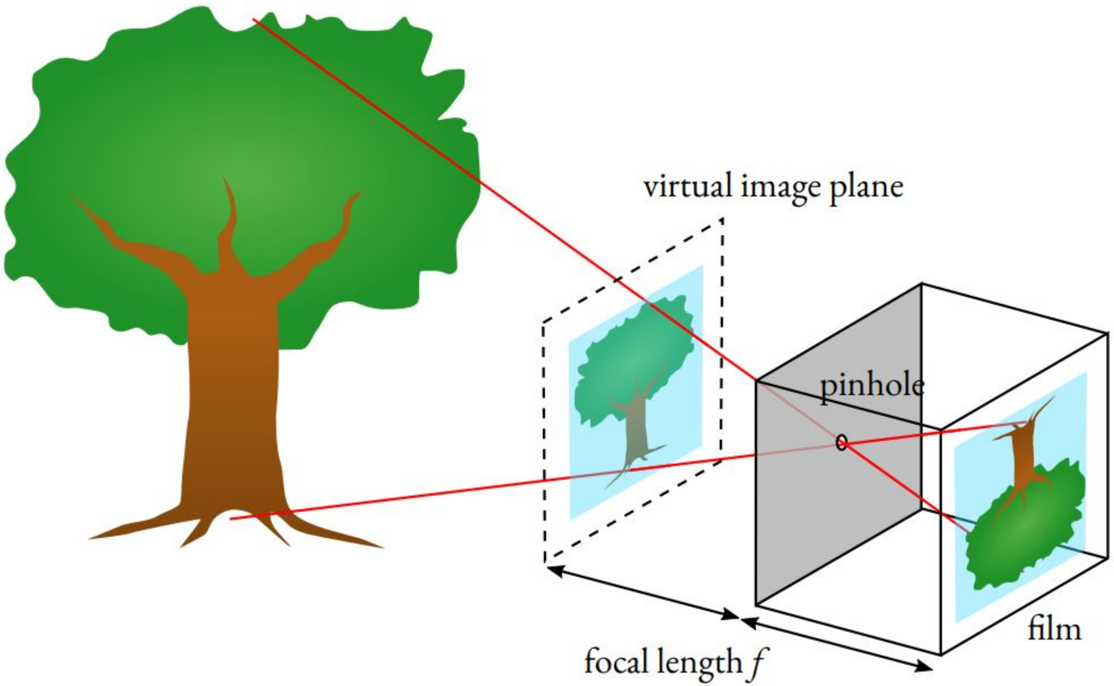


(a) Angle -1 (b) Angle 0 (c) Angle +1

GVF-Snakes

- Algorithm to detect outline
- Success ensured by initial contour and preprocessing steps

Pinhole camera model



Pinhole camera model

- Point in camera reference frame:

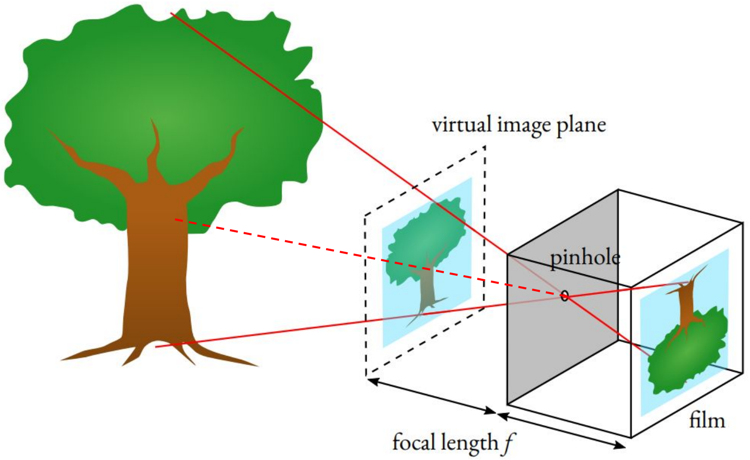
$$\mathbf{r}' = [x', y', z']$$

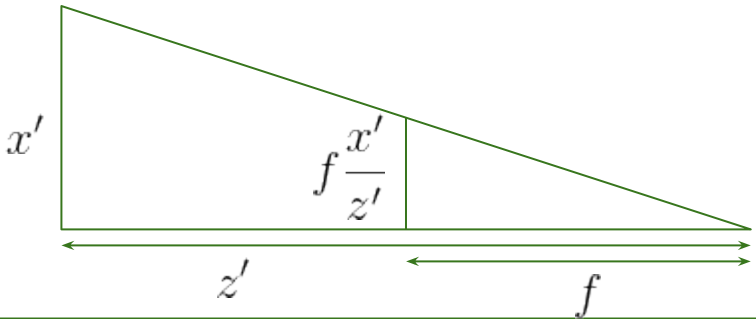
- Projection equations:

$$f\frac{x'}{z'} = u - u_0$$

$$f\frac{y'}{z'} = v - v_0$$

(u_0, v_0) center of image plane





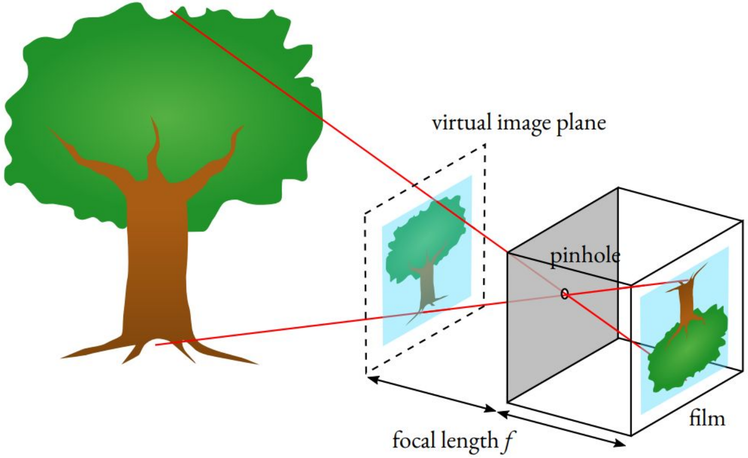
Pinhole camera model

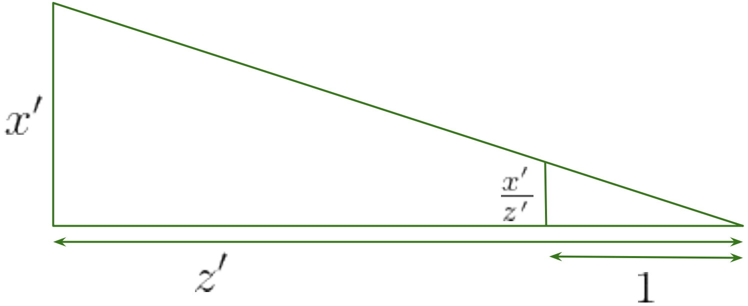
- Point in camera reference frame:

$$\mathbf{r}' = [x', y', z']$$

- Normalized image coordinates:

$$\frac{1}{z'}\mathbf{r}' = \begin{bmatrix} x'/z' \\ y'/z' \\ z'/z' \end{bmatrix} = \mathbf{y}$$





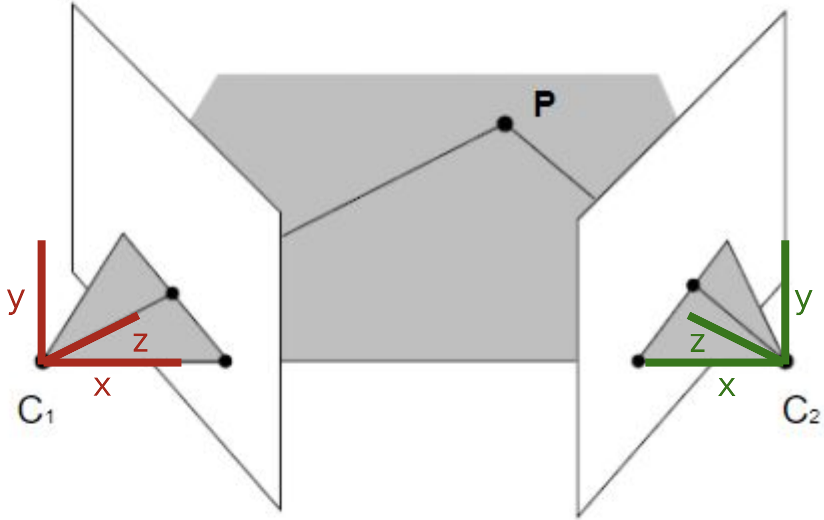
3D Contour Reconstruction

Two-view geometry

- Two camera's aiming at the same point $\mathbf{P}$

$$\mathbf{r}' = [x', y', z']$$
$$\mathbf{r}'' = [x'', y'', z'']$$
$$\mathbf{t} = [t_1, t_2, t_3]$$

$$\mathbf{r}'' = R\mathbf{r}' + \mathbf{t}$$



Essential Matrix

- $$\mathbf{r}'' = R\mathbf{r}' + \mathbf{t}$$
  $$z''\mathbf{y}'' = z'R\mathbf{y}' + \mathbf{t}$$
  $$0 = (\mathbf{y}'')^T E\mathbf{y}'$$

3D Contour Reconstruction

Essential Matrix

- $$\begin{aligned} \mathbf{r}'' &= R\mathbf{r}' + \mathbf{t} \\ z''\mathbf{y}'' &= z'R\mathbf{y}' + \mathbf{t} \\ 0 &= (\mathbf{y}'')^T E\mathbf{y}' \end{aligned}$$

- Where E is a 3x3 matrix called the Essential Matrix defined by $E = [\mathbf{t}]_\times R$

$$\mathbf{t} \times R = [\mathbf{t}]_\times R, \quad [\mathbf{t}]_\times = \begin{bmatrix} 0 & -t_3 & t_2 \\ t_3 & 0 & -t_1 \\ -t_2 & t_1 & 0 \end{bmatrix}$$

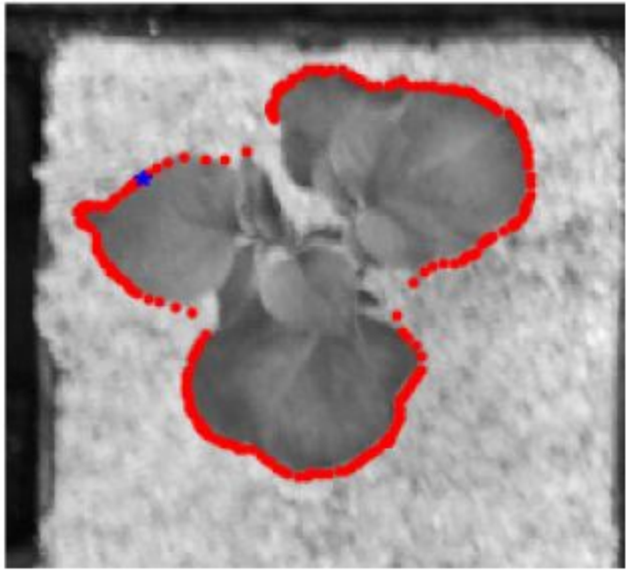
3D Contour Reconstruction

Essential Matrix

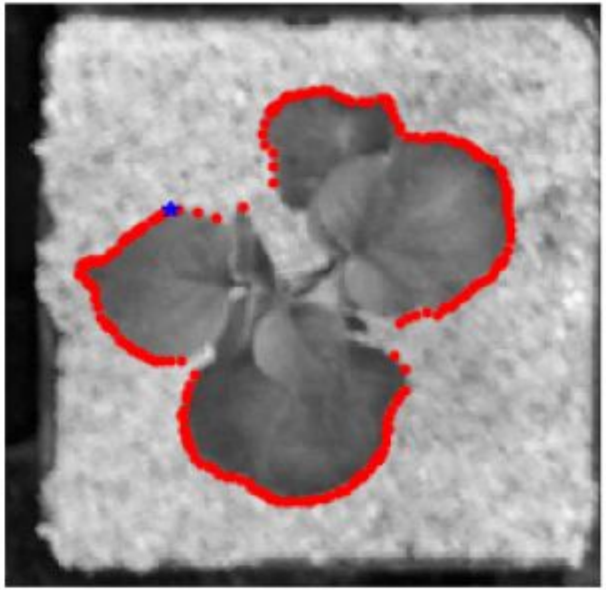
- Determine E from $(\mathbf{y}'')^T E \mathbf{y}' = 0$
- $Y\mathbf{e} = \mathbf{0}$, nx9 matrix Y
- Minimum of 8 point correspondences
- Find nullspace of Y using Singular Value Decomposition
  $U, D, V^T = \mathrm{svd}(Y)$
  in column of V

3D Contour Reconstruction

Point matching



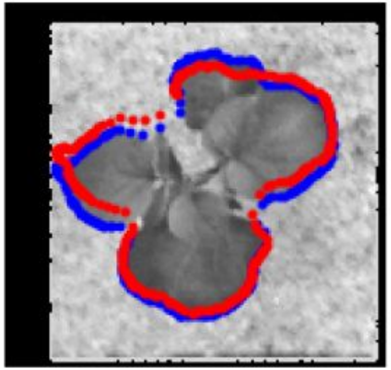
(a) Image and contour 1



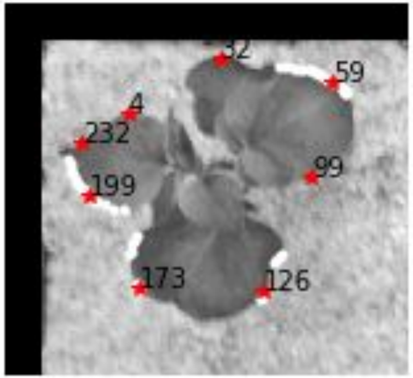
(b) Image and contour 2

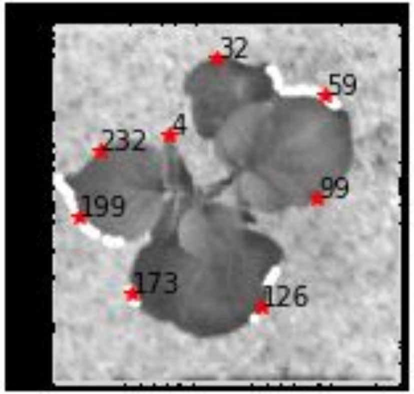
3D Contour Reconstruction

Point matching



- Rough alignment
- Choose 8 random points on contour
  and find the corresponding closest points
- Compute E and check
  $(\mathbf{y}'')^T E \mathbf{y}' < \varepsilon$
- Continue until satisfied





3D Contour reconstruction

- Obtain rotation and translation via another Singular Value Decomposition of E

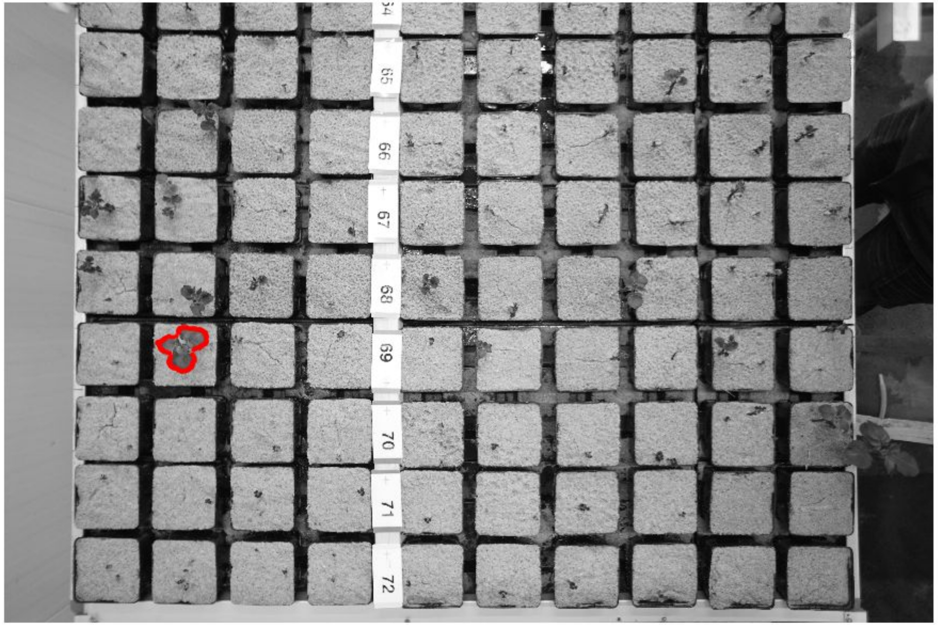
- Retrieve depth coordinate

$$\mathbf{y}'' = \frac{1}{z''}\mathbf{r}'' = \frac{R\mathbf{r}' + \mathbf{t}}{\mathbf{e}_3^T(R\mathbf{r}' + \mathbf{t})}$$

$$\mathbf{y}'' = \frac{Rz'\mathbf{y}' + \mathbf{t}}{\mathbf{e}_3^T(Rz'\mathbf{y}' + \mathbf{t})}$$

$$z' = -\frac{\mathbf{y}'^T R^T \left(\mathbf{y}''\mathbf{e}_3^T - I\right)^T \left(\mathbf{y}''\mathbf{e}_3^T - I\right)\mathbf{t}}{\mathbf{y}'^T R^T \left(\mathbf{y}''\mathbf{e}_3^T - I\right)^T \left(\mathbf{y}''\mathbf{e}_3^T - I\right) R\mathbf{y}'}$$

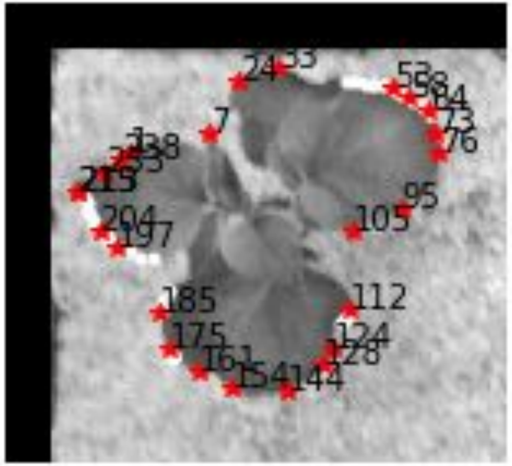
3D Contour reconstruction

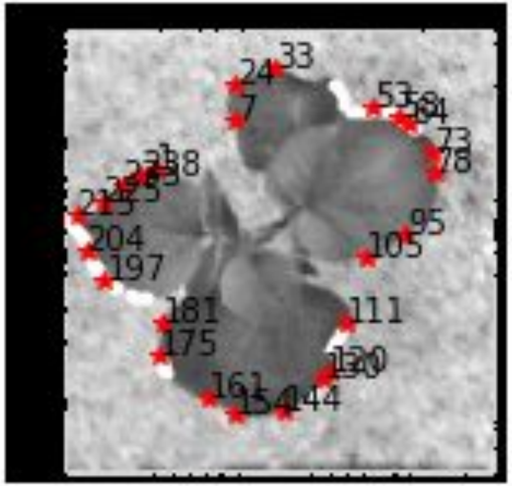


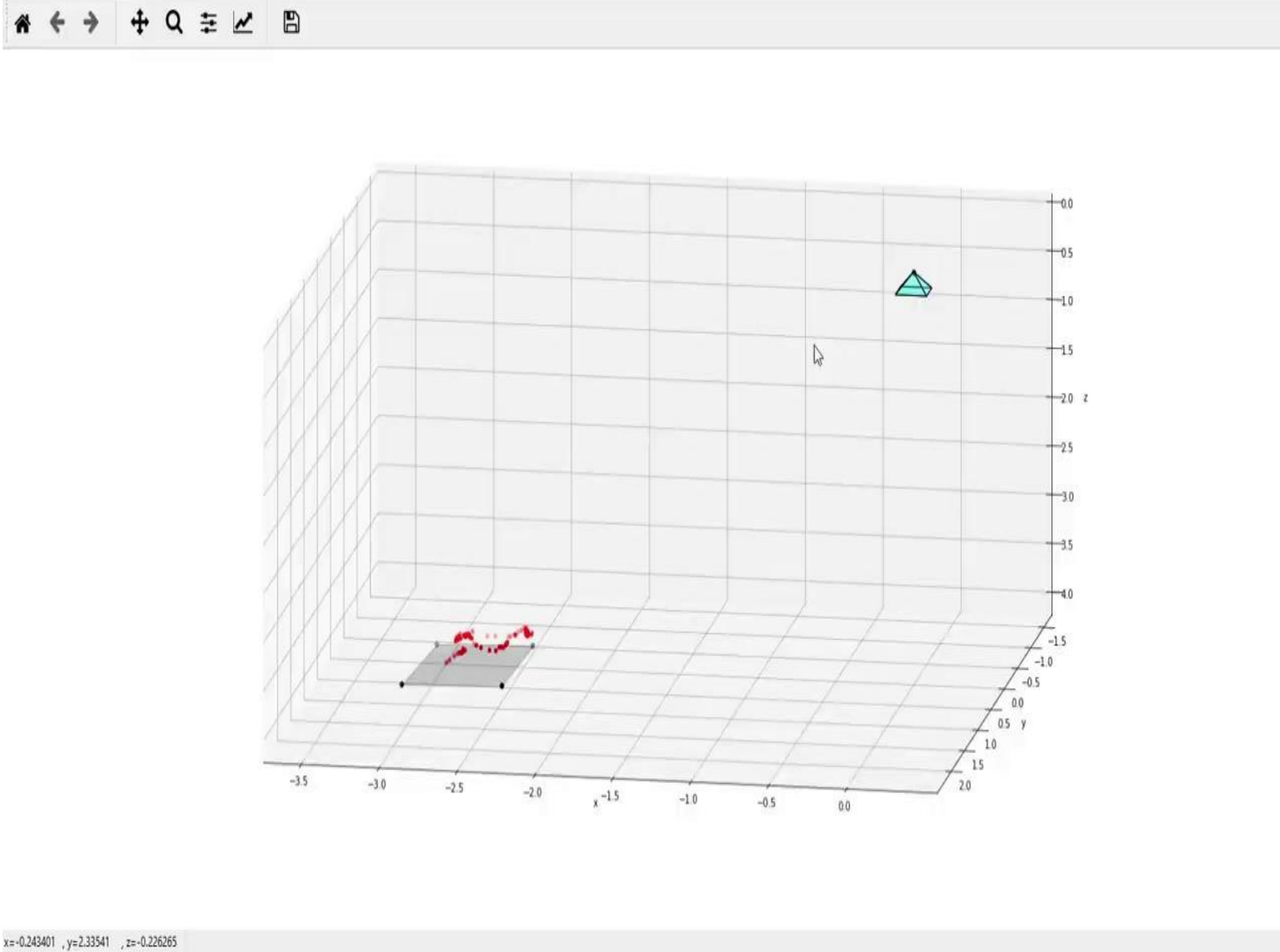
3D Contour reconstruction

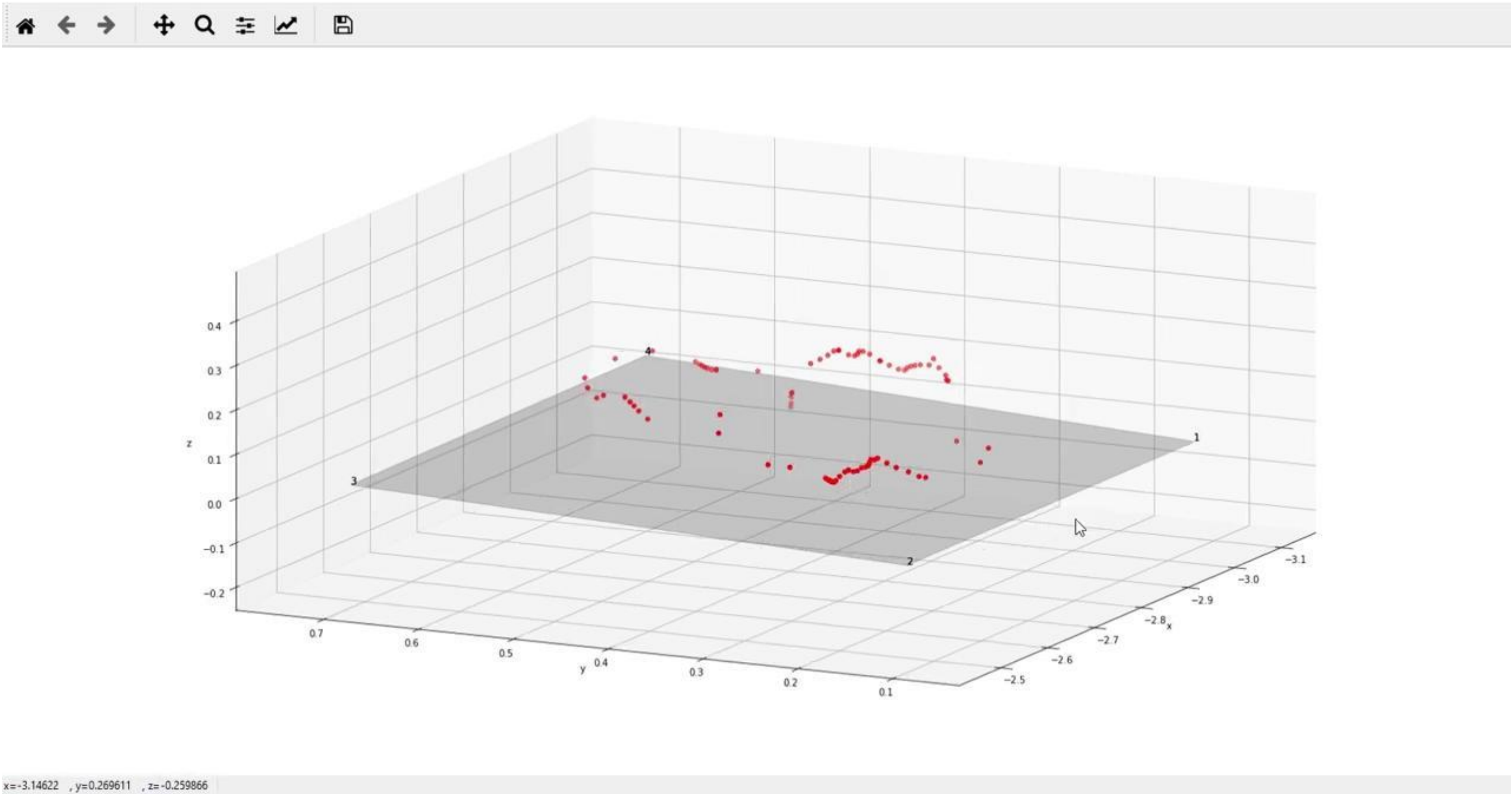
$$R = \begin{bmatrix} 1 & 0.015 & -0.010 \\ -0.014 & 1 & 0.025 \\ 0.011 & -0.025 & 1 \end{bmatrix}$$

$$\mathbf{t} = \begin{bmatrix} 0.08 \\ 0.99 \\ -0.11 \end{bmatrix}$$



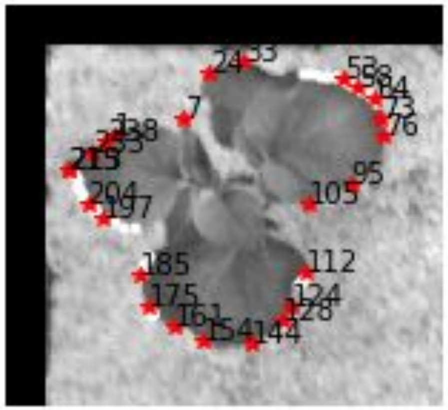


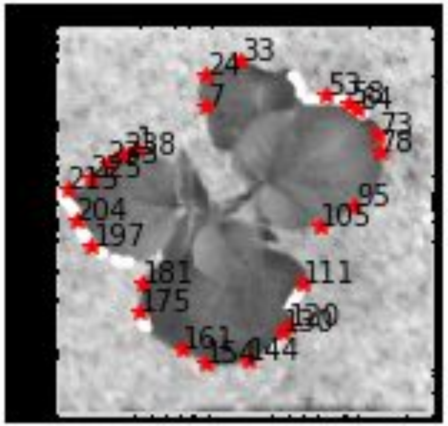

0.0
0.5
1.0
1.5
2.0 z
2.5
3.0
3.5
4.0
-1.5
-1.0
-0.5
0.0
0.5 y
1.0
1.5
2.0
-3.5
-3.0
-2.5
-2.0
x -1.5
-1.0
-0.5
0.0
x=-0.243401 , y=2.33541 , z=-0.226265

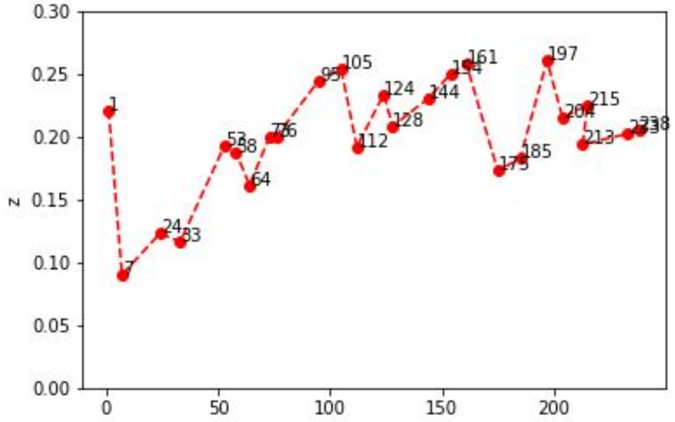


0.4
0.3
0.2
z
0.1
0.0
−0.1
−0.2
0.7
0.6
0.5
y
0.4
0.3
0.2
0.1
−2.5
−2.6
−2.7
−2.8
x
−2.9
−3.0
−3.1
1
2
3
4
x=-3.14622 , y=0.269611 , z=-0.259866

3D Contour reconstruction





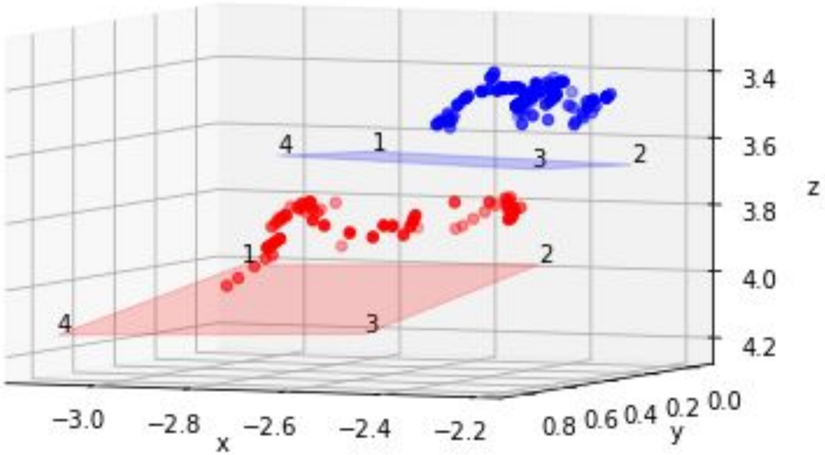


Observation of growth

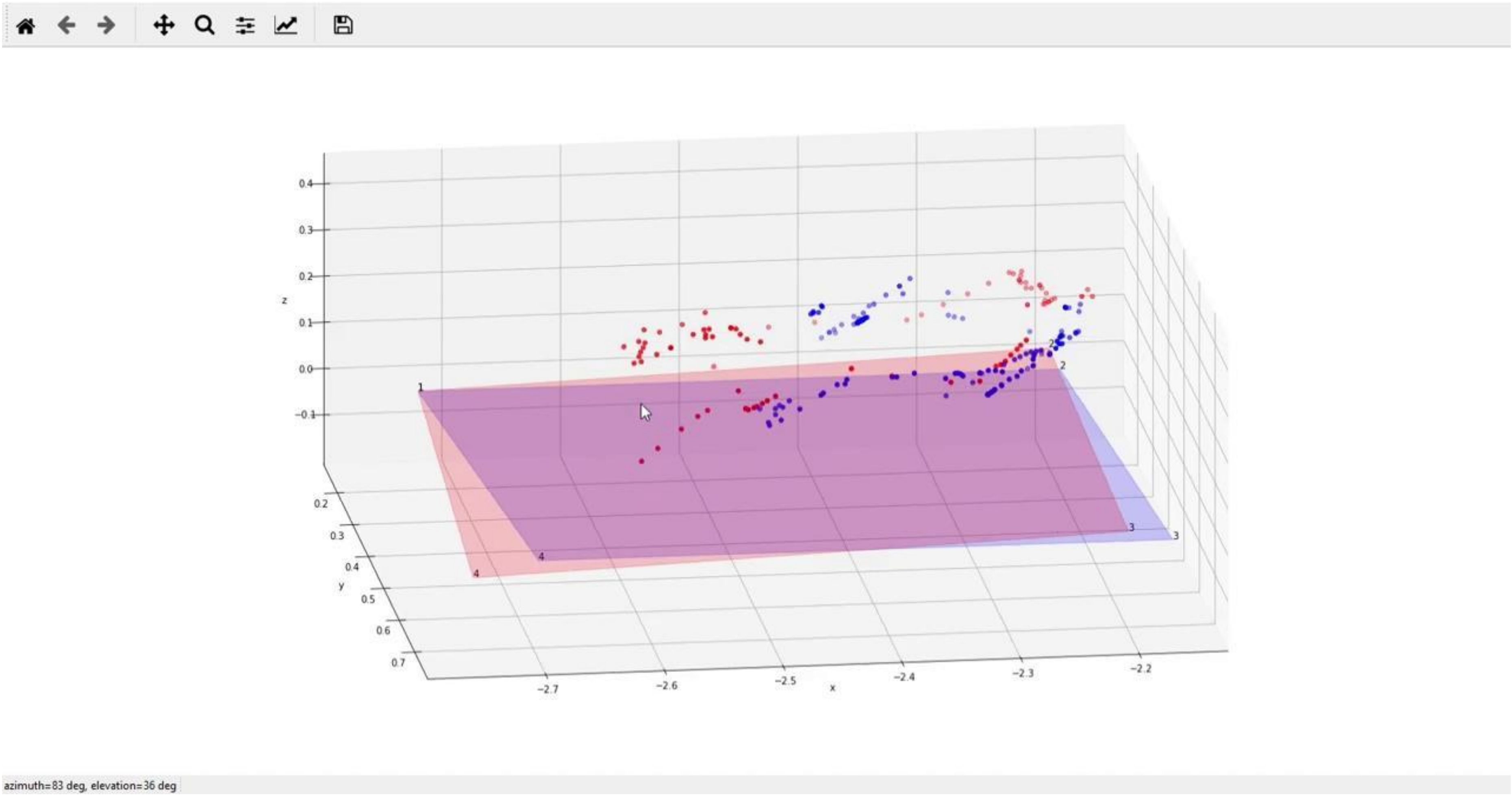
3D Contour Reconstruction

Misalignment

- $\mathbf{r}'(\tau_1) = aR\mathbf{r}'(\tau_2) + \mathbf{t}$
- Alignment based solely on corner points

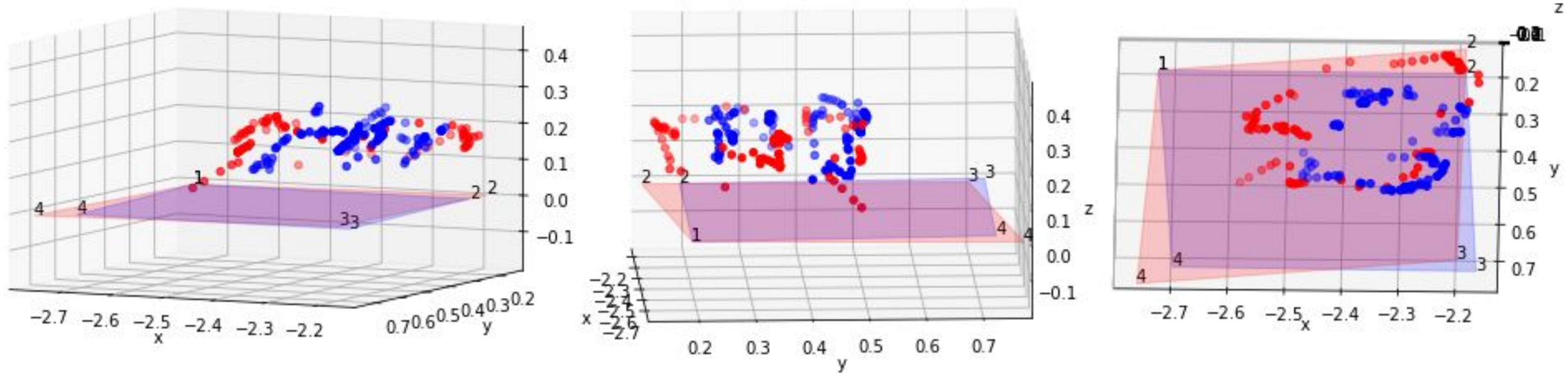


3D Contour Reconstruction



z
0.4
0.3
0.2
0.1
0.0
-0.1
y
0.2
0.3
0.4
0.5
0.6
0.7
x
-2.7
-2.6
-2.5
-2.4
-2.3
-2.2
1
2
2
3
3
4
4
azimuth=83 deg, elevation=36 deg

Observation of growth



3D Reconstruction

- 3D reconstruction up to scale
- In camera reference frame
- SVD
- Alignment of plant’s container

Double Snakes

- Combine previous problems
- Evolve both snakes simultaneously and match points on contour

- Minimize the functional

$$\Phi[\mathbf{y}_1, \mathbf{y}_2] = \int_0^1 \left[\frac{\alpha}{2} \left(\|\mathbf{y}_1'\|^2 + \|\mathbf{y}_2'\|^2 \right) + \frac{\beta}{2} \left(\|\mathbf{y}_1''\|^2 + \|\mathbf{y}_2''\|^2 \right) + \frac{1}{2} \left(\mathbf{y}_2^T E \mathbf{y}_1 \right)^2 \right] \mathrm{d}s$$

$$\frac{\partial \mathbf{y}_1}{\partial t} = \alpha \frac{\partial^2 \mathbf{y}_1}{\partial s^2} - \beta \frac{\partial^4 \mathbf{y}_1}{\partial s^4} - E^T \mathbf{y}_2 \mathbf{y}_2^T E \mathbf{y}_1 + \mathbf{F}(\mathbf{y}_1),$$

$$\frac{\partial \mathbf{y}_2}{\partial t} = \alpha \frac{\partial^2 \mathbf{y}_2}{\partial s^2} - \beta \frac{\partial^4 \mathbf{y}_2}{\partial s^4} - E \mathbf{y}_1 \mathbf{y}_1^T E^T \mathbf{y}_2 + \mathbf{F}(\mathbf{y}_2).$$

Convexity

- When does $(\mathbf{y}'')^T E \mathbf{y}' = 0$ hold?

- $(\mathbf{y}'')^T E = \mathbf{0}$
  $E\mathbf{y}' = \mathbf{0}$

  The left and right nullspace of E

Double Snakes

Double Snakes

- Simultaneously updating both contours
- Convexity of the essential matrix

Conclusion

- GVF-Snakes algorithm to detect contour
- 3D contour reconstruction up to scale
- Observation of growth due to alignment of plant's container
- Introduction of Double Snakes

Recommendations

- Stabilizing the estimation of the essential matrix
- More advanced camera model
- Improve alignment of plant's container
- Explore convexity of the coplanarity constraint

Questions?