GENERATIONS / VANCOUVER 12-16 AUGUST SIGGRAPH2018

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

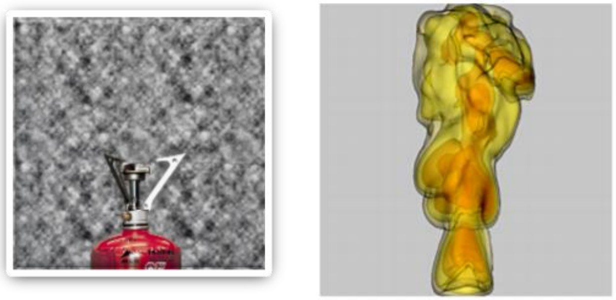
Space-time Tomography for Continuously Deforming Objects

Guangming Zang, Ramzi Idoughi, Ran Tao, Gilles Lubineau, Peter Wonka, Wolfgang Heidrich,
King Abdullah University of Science And Technology

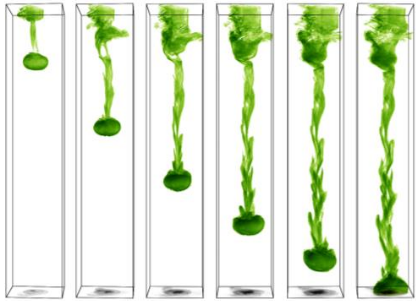


جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

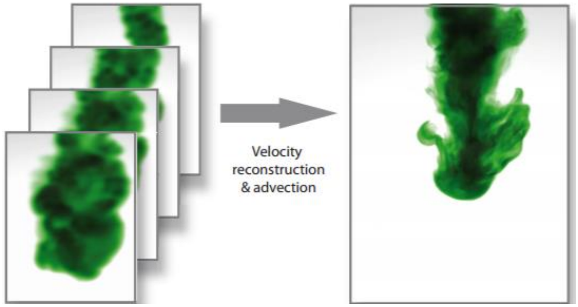
Tomography in graphics



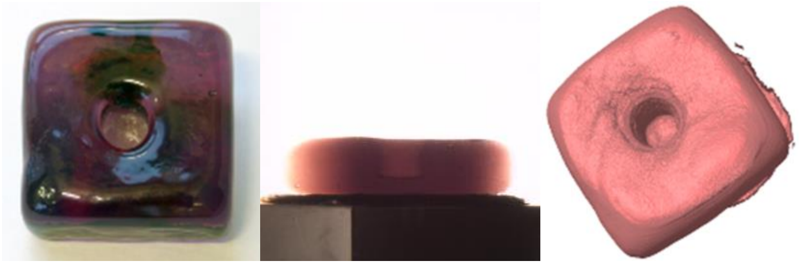
Gas Flows capture
[Atcheson et al. 2008]



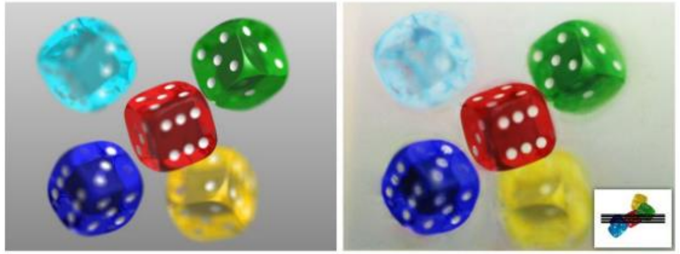
Fluid scanning
[Gregson et al. 2012]



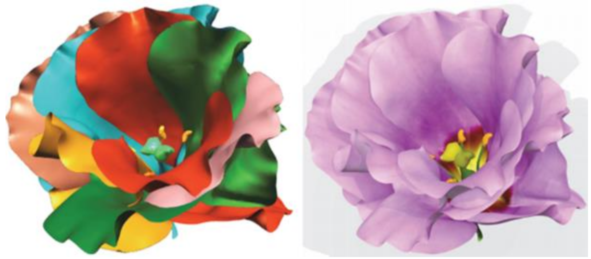
Velocity reconstruction
[Gregson et al. 2014]



Transparent reconstruction
[Trifonov et al. 2006]

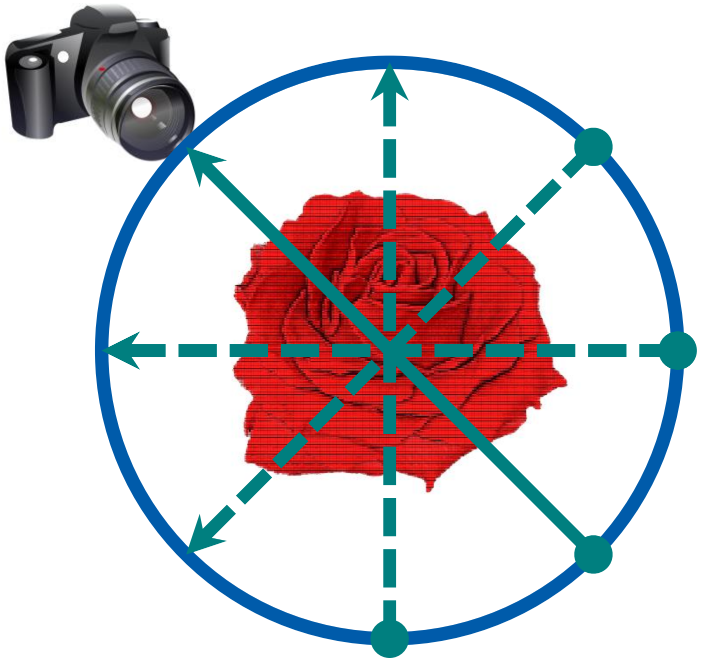


Multi-layer 3D display
[Wetzstein et al. 2011]



Flower modeling
[Ijiri et al. 2014]

Motivation



Unknowns: ~ 500^3 voxels
Equations: 2M pixels × Number of projections

Large number of projections + priors

Motivation

Time for one projection: **~ 5 s**

Is it possible to scan continuously deforming objects ?

Motivation

Classical reconstruction using 5520 projections (duration: 9h32m)

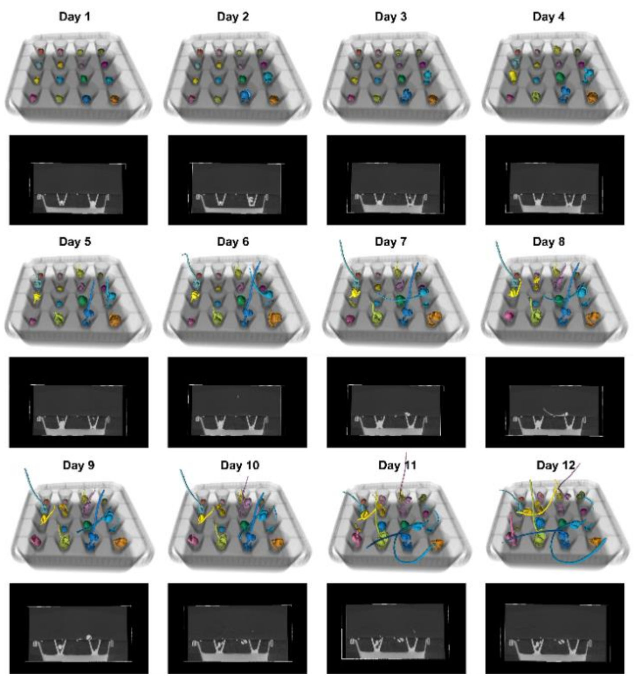
Before scan

After scan

Wilting rose

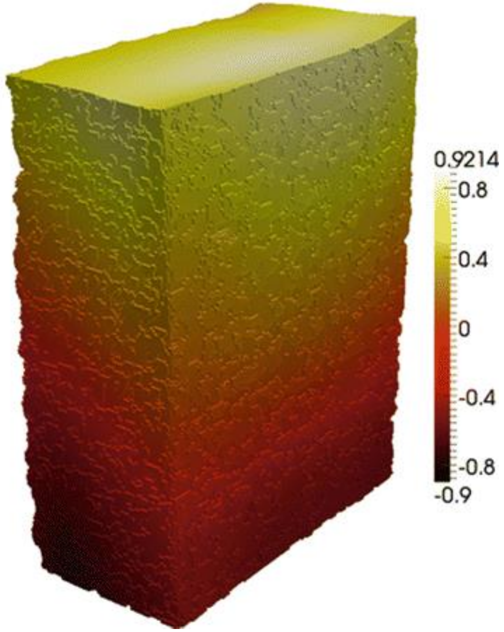
Related work

Discrete deformations / Key framing



Growing plant animation

[Kato et al. 2017]



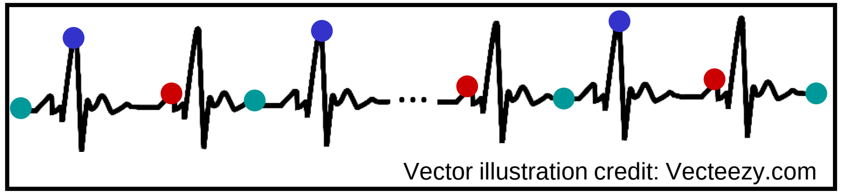
Digital Volume Correlation to retrieve the deformation field

[Hild et al. 2014]

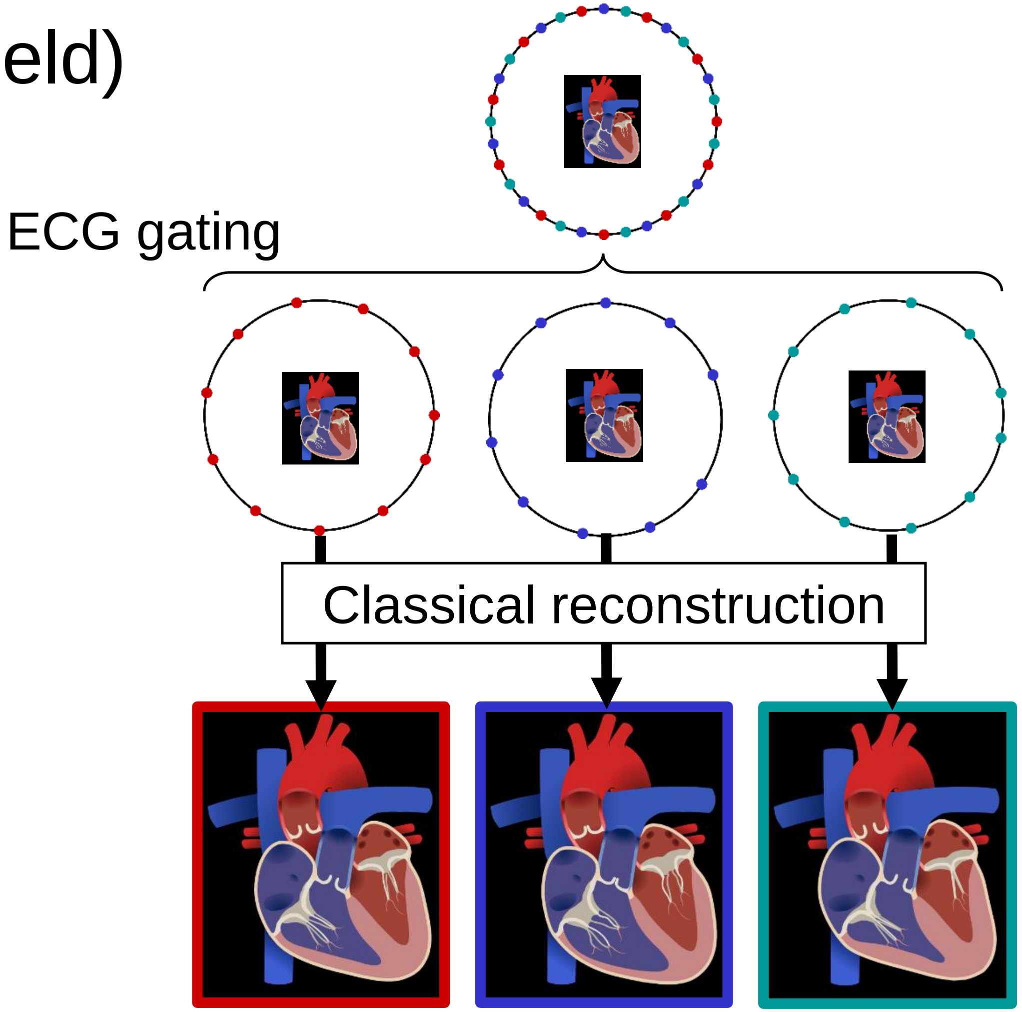
جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Related work

Periodic deformations (Medical field)



Electrocardiography (ECG)



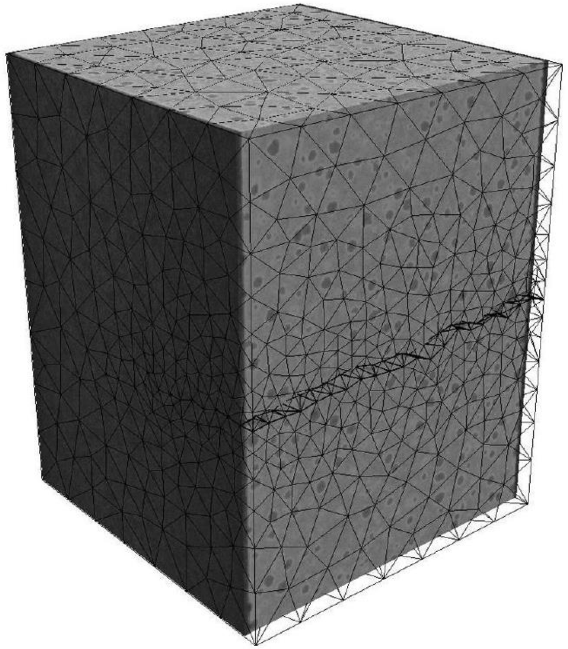
credit: austincc.edu

[Chen et al. 2012]

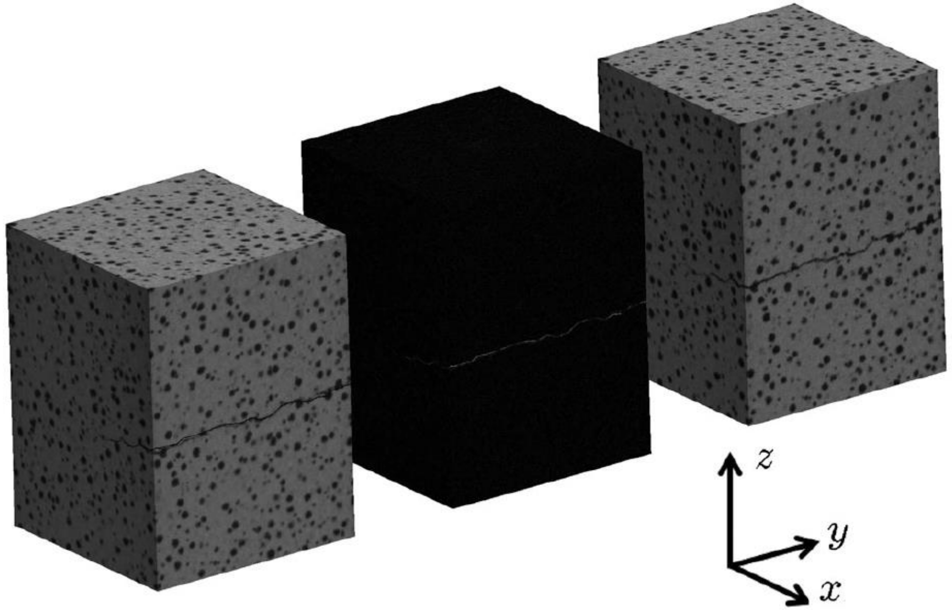
Related work

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

General deformations (parametric approach)



Use of basis-functions approach
(e.g. finite element framework)



The volume is advected from a reference, using an estimated displacement.

[Taillandier-Thomas et al. 2016]

Objective

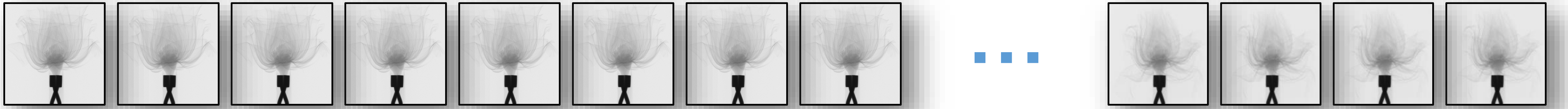
Space-time tomography reconstruction

Before scan

After scan

Wilting rose

Space-time tomography



<u>Assumption</u>: relatively slow deformations (less than 6 voxels/minute)

Space-time tomography

Frame 01

Frame 02

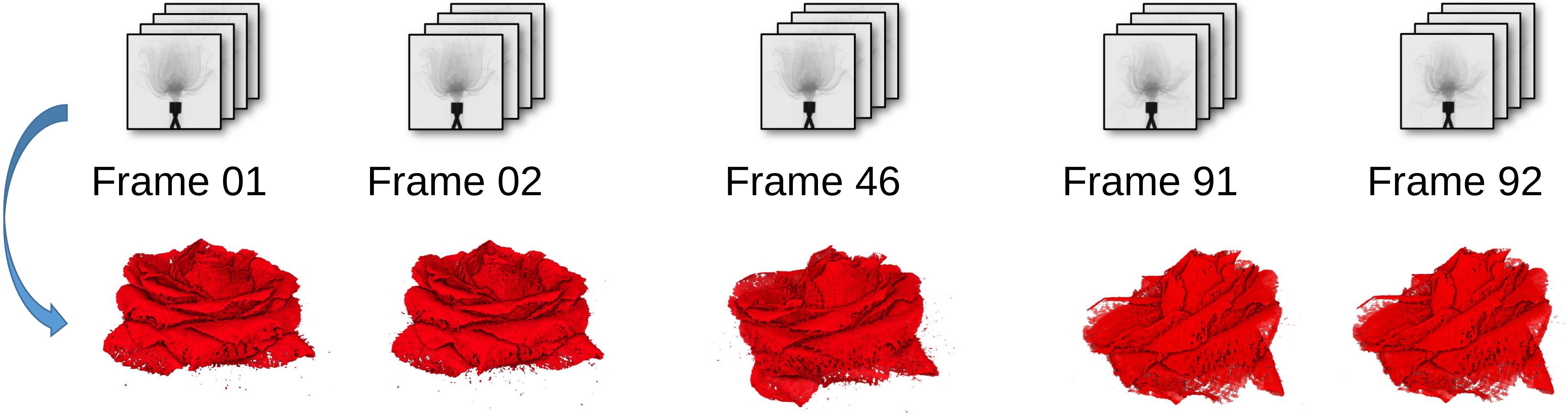
Frame 46

Frame 91

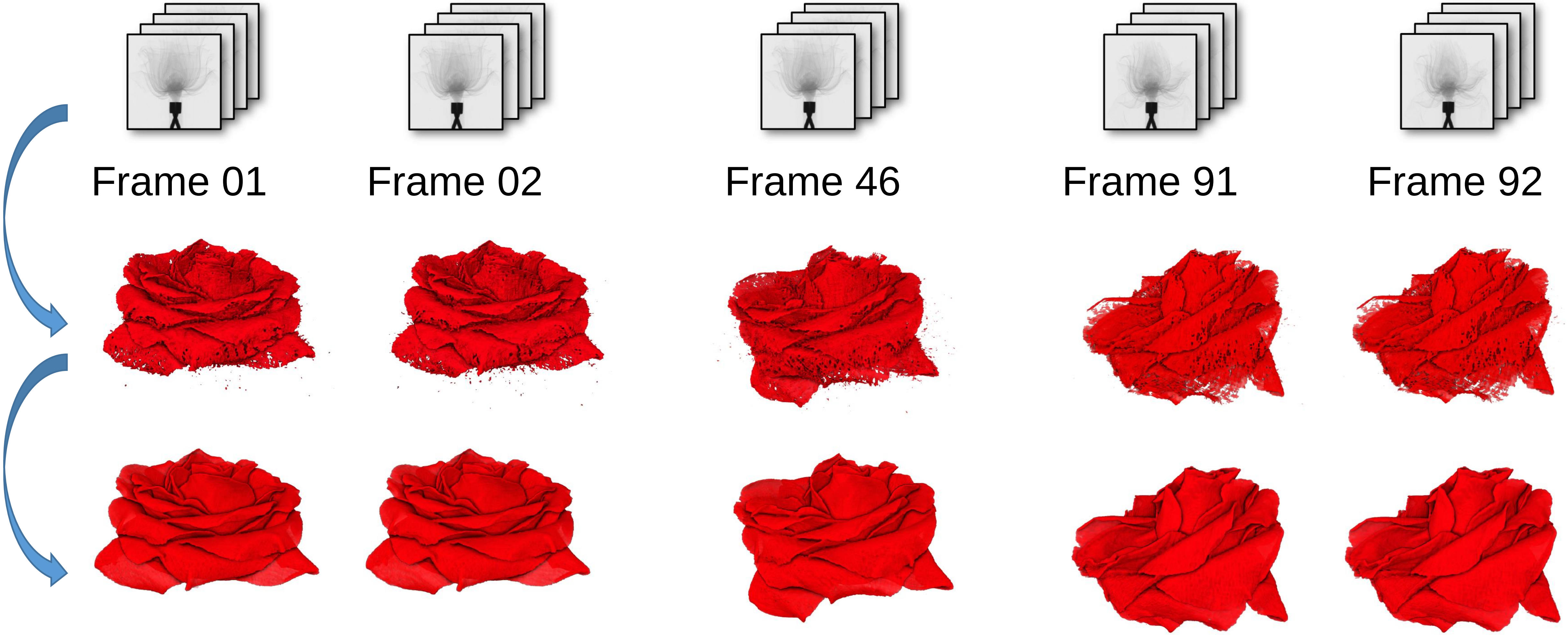
Frame 92

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

Space-time tomography



Space-time tomography

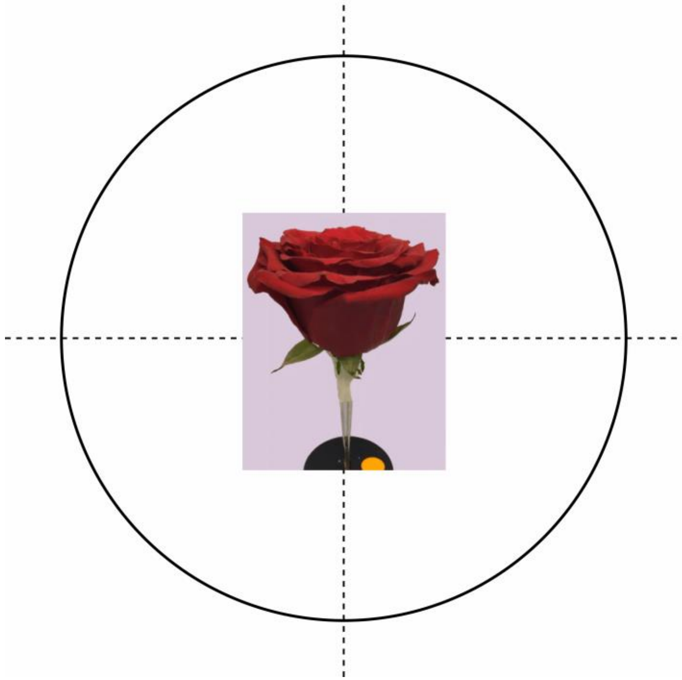


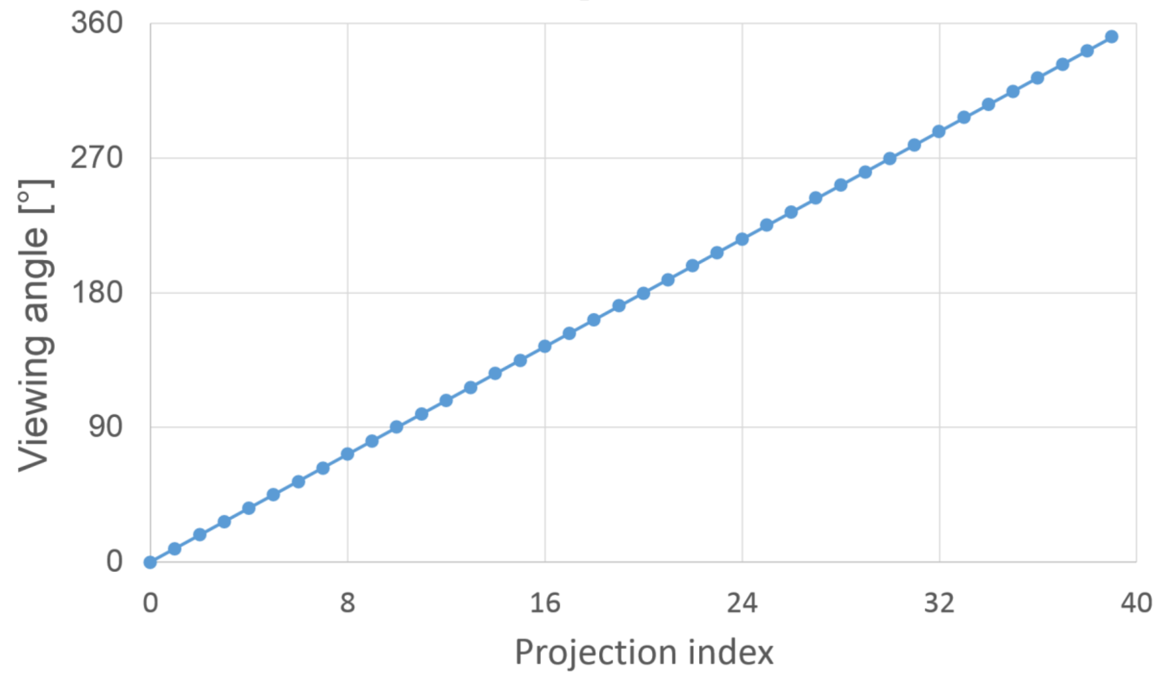
Overview

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

- Data acquisition
- 4D tomographic reconstruction
- Results

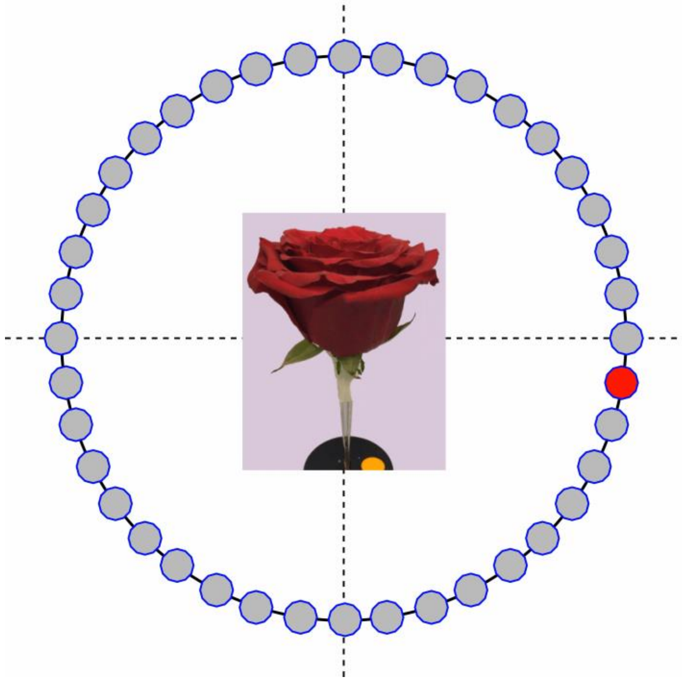
Data acquisition

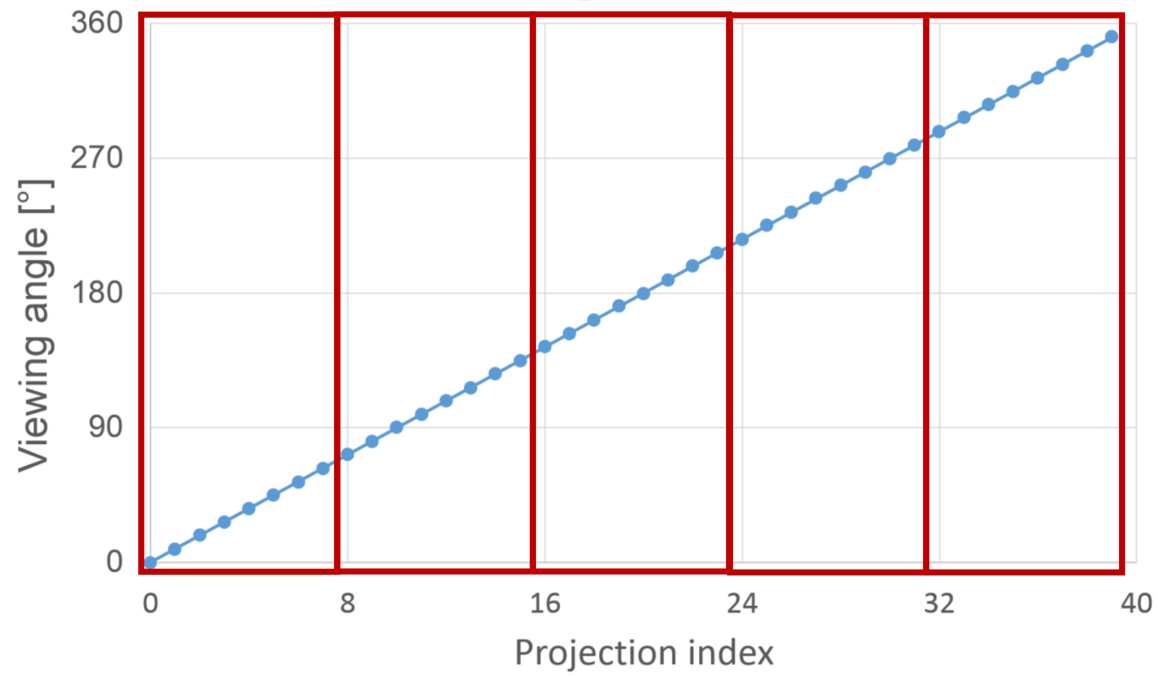




Classical acquisition strategy

Data acquisition

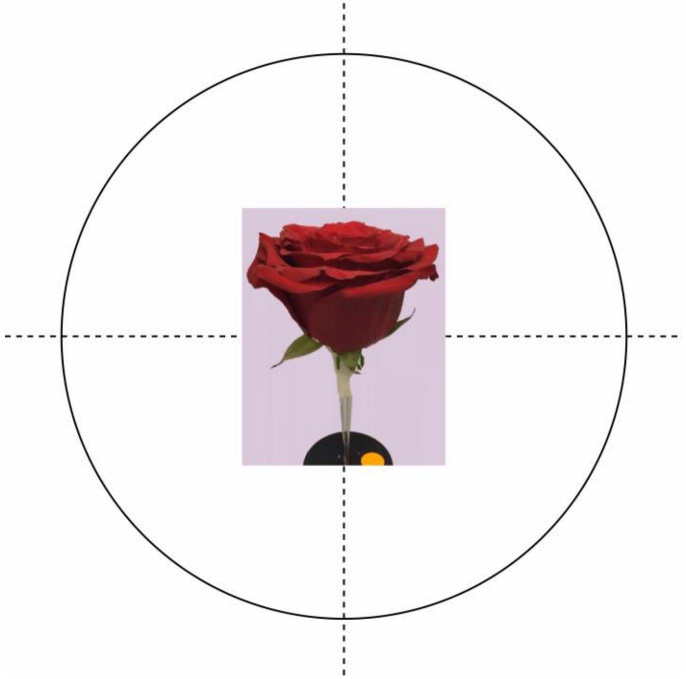


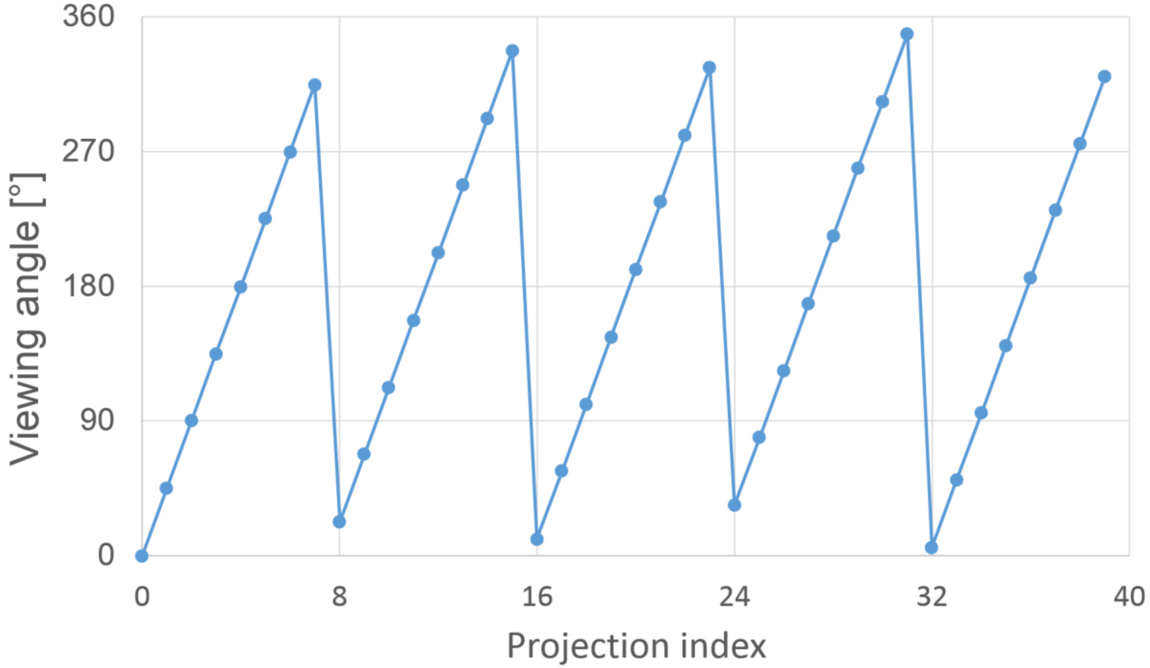


Classical acquisition strategy

Data acquisition

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

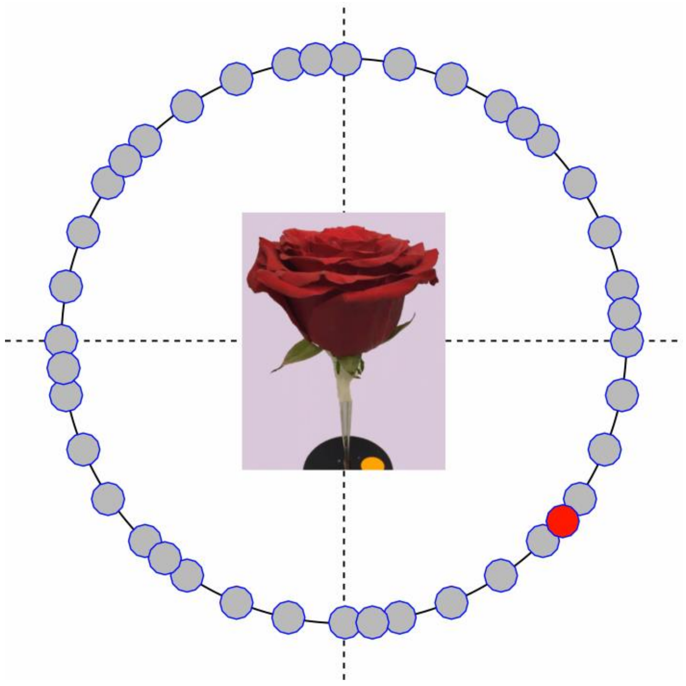


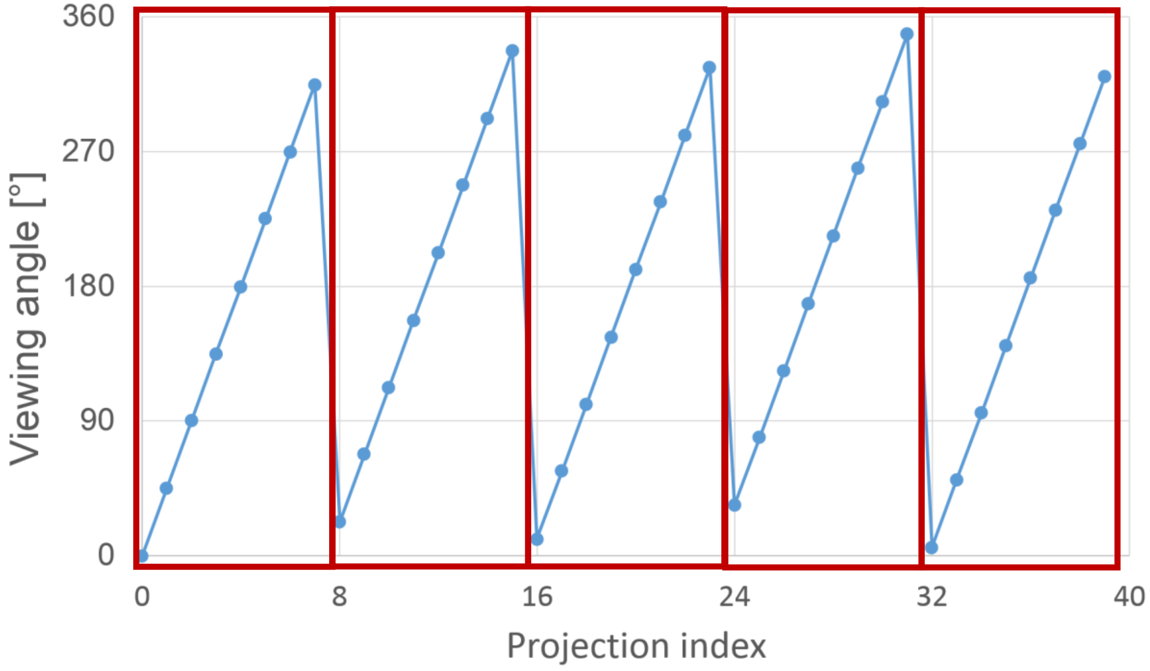


Low-discrepancy acquisition strategy

(Van der Corupt sequence)

Data acquisition





Low-discrepancy acquisition strategy

(Van der Corupt sequence)

Overview

- Data acquisition
- 4D tomographic reconstruction
- Results

Image formation model

X-ray path: Ω_i

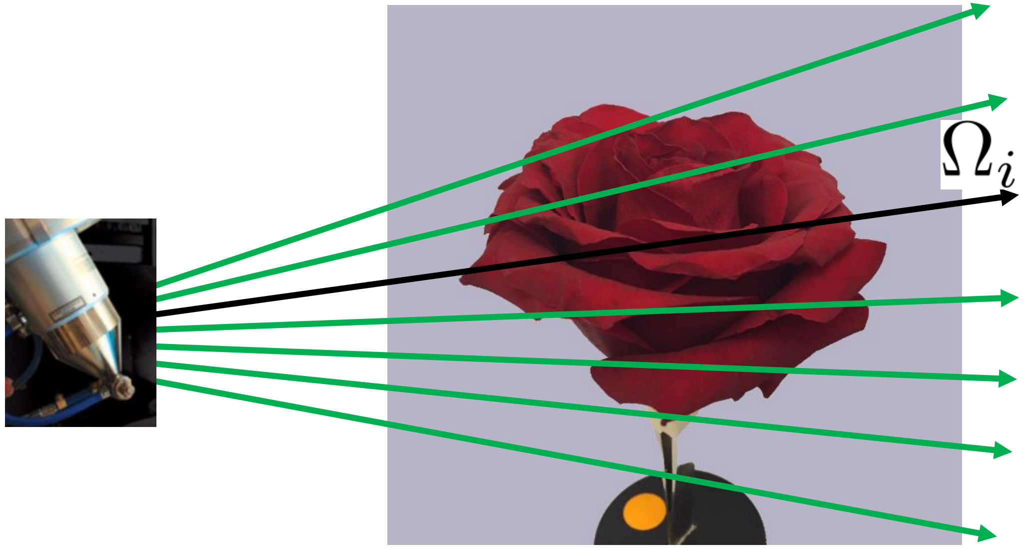


Image formation model

X-ray path: Ω_i

Unknown field: $f(x)$

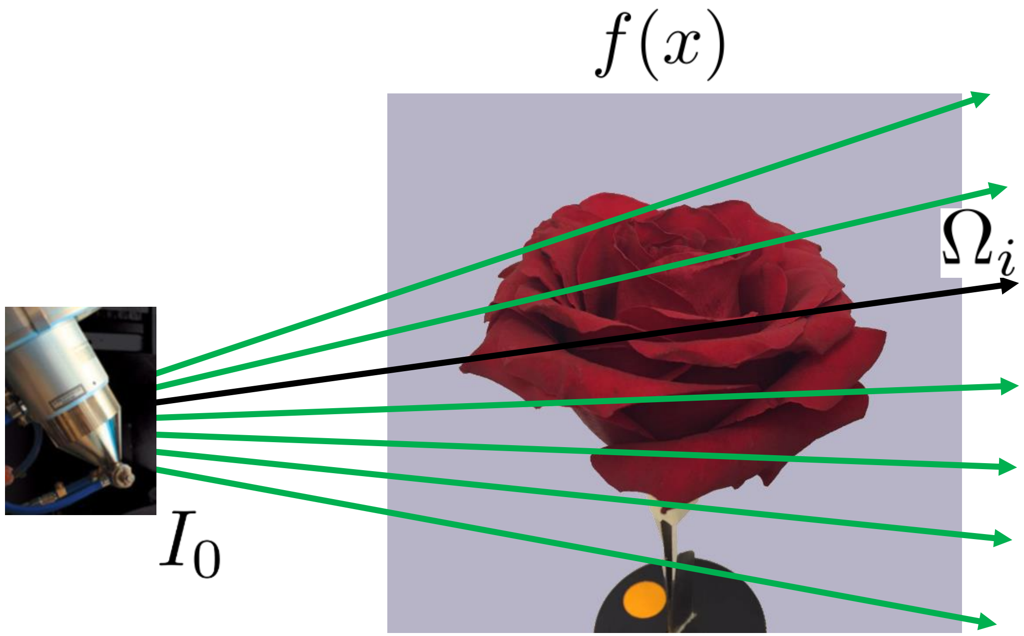


Image formation model

X-ray path: Ω_i

Unknown field: $f(x)$

Measurement: p_i

$$\int_{\Omega_i} f(x)\,\mathrm{d}\Omega_i = \underbrace{-log(I_i/I_0)}_{p_i}$$

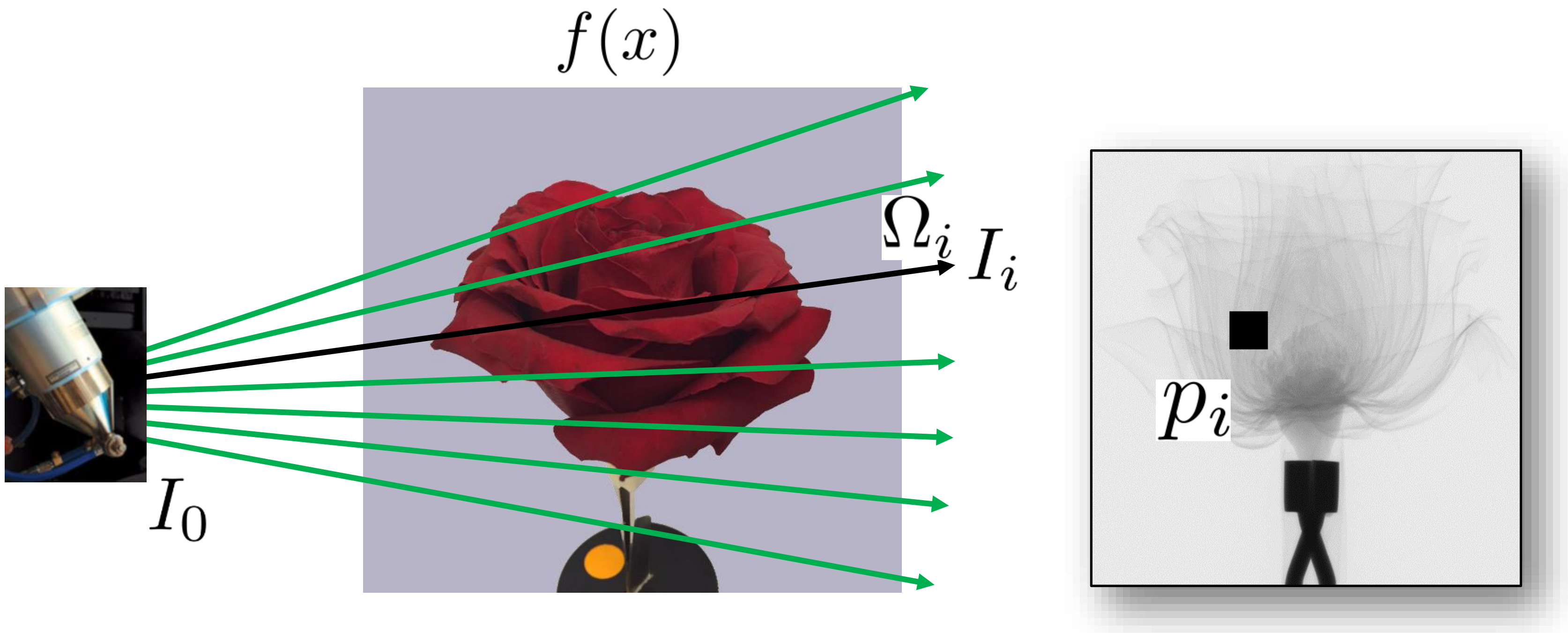


Image formation model

X-ray path: Ω_i

Unknown field: $f(x)$

Measurement: p_i

$$\sum_j f_j A_{ij} = p_i$$

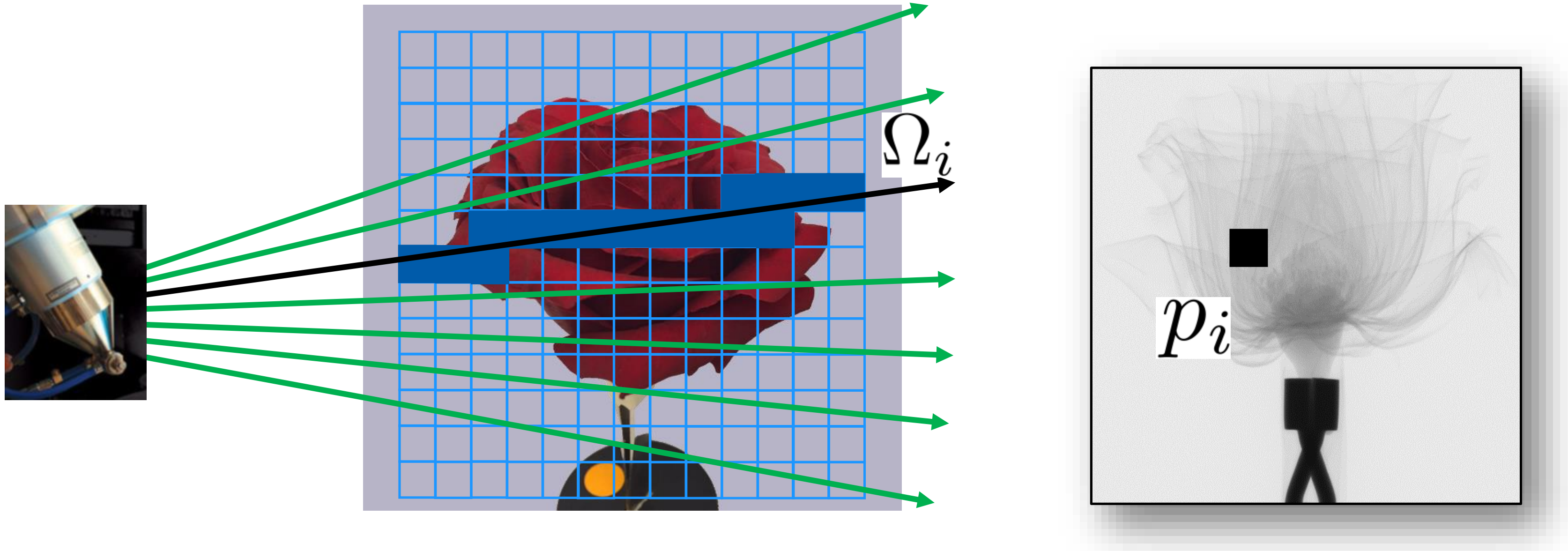


Image formation model

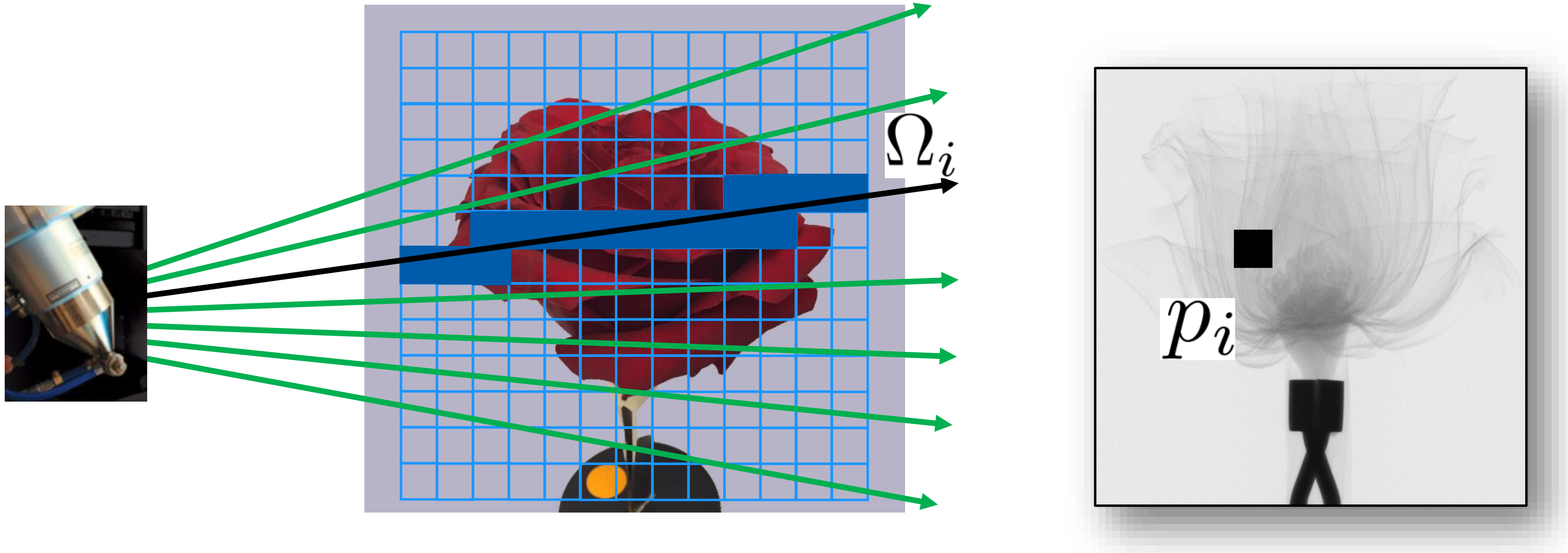
X-ray path: Ω_i

Unknown field: $f(x)$

Measurement: p_i

$$\sum_j f_j A_{ij} = p_i$$

$$A_t f_t = p_t$$



Negligible deformation in sequential projections!

Space-time tomography

Frame 01 Frame 02 Frame 46 Frame 91 Frame 92

$$\underbrace{\begin{pmatrix} \mathbf{A}_1 & & & \\ & \ddots & & \\ & & \mathbf{A}_t & \\ & & & \ddots \\ & & & & \mathbf{A}_{N_t} \end{pmatrix}}_{\mathbf{A}} \cdot \underbrace{\begin{pmatrix} \mathbf{f}_1 \\ \vdots \\ \mathbf{f}_t \\ \vdots \\ \mathbf{f}_{N_t} \end{pmatrix}}_{\mathbf{f}} = \underbrace{\begin{pmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_t \\ \vdots \\ \mathbf{p}_{N_t} \end{pmatrix}}_{\mathbf{p}}$$

Linear system

- Sparse system
- Memory consuming
- Ill-posed problem

$$
\underbrace{\left(\begin{array}{c|c|c}
\mathbf{A}_1 & & \\
\hline
 & \begin{matrix}\ddots & & \\ & \mathbf{A}_t & \\ & & \ddots\end{matrix} & \\
\hline
 & & \mathbf{A}_{N_t}
\end{array}\right)}_{\mathbf{A}}
\cdot
\underbrace{\left(\begin{array}{c}
\mathbf{f}_1 \\
\hline
\vdots \\
\mathbf{f}_t \\
\vdots \\
\hline
\mathbf{f}_{N_t}
\end{array}\right)}_{\mathbf{f}}
=
\underbrace{\left(\begin{array}{c}
\mathbf{p}_1 \\
\hline
\vdots \\
\mathbf{p}_t \\
\vdots \\
\hline
\mathbf{p}_{N_t}
\end{array}\right)}_{\mathbf{p}}
$$

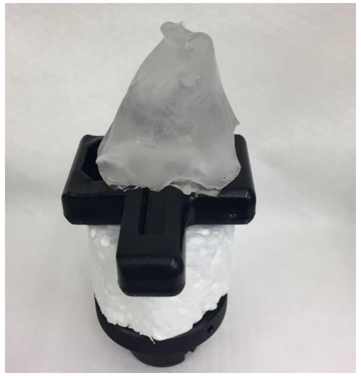
Radon Transform Frames Measurements

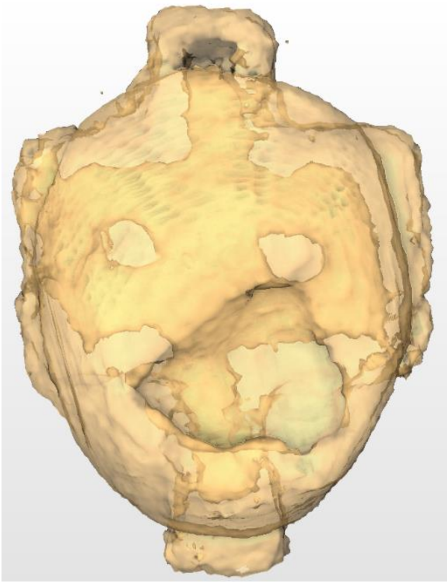
Linear system

Space time tomography

- Non-parametric and matrix-free
- Alternating, multi-scale optimization
- Flexibility: priors incorporating and implementation

Priors

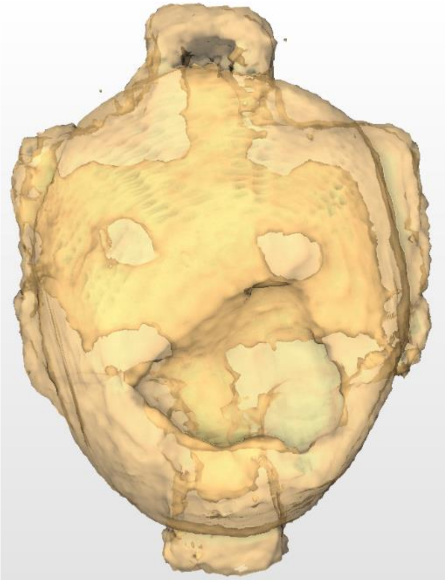


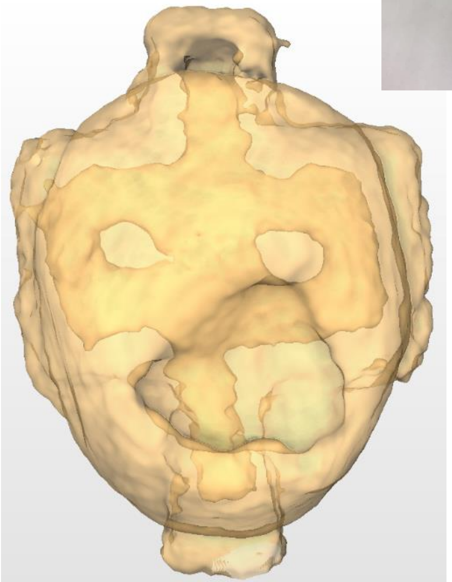


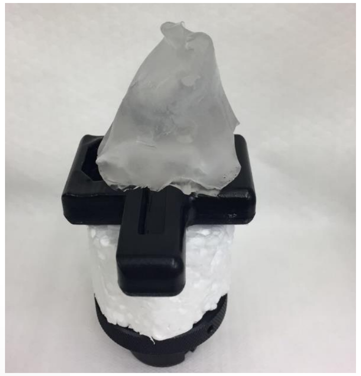
Tomography

$$\|\mathbf{A}_t \mathbf{f}_t - \mathbf{p}_t\|_2^2$$

Priors







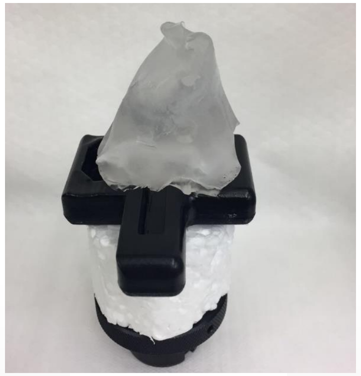
Tomography

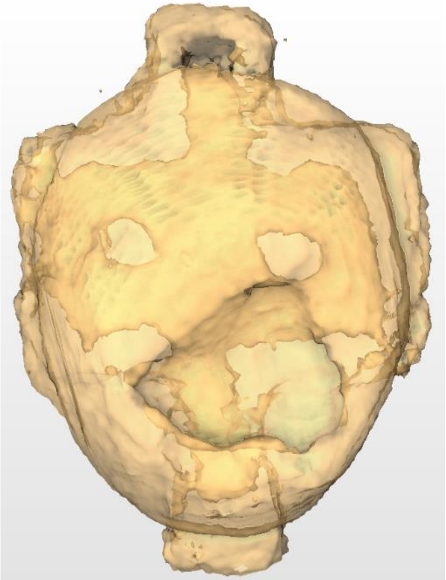
$$||\mathbf{A}_t \mathbf{f}_t - \mathbf{p}_t||_2^2$$

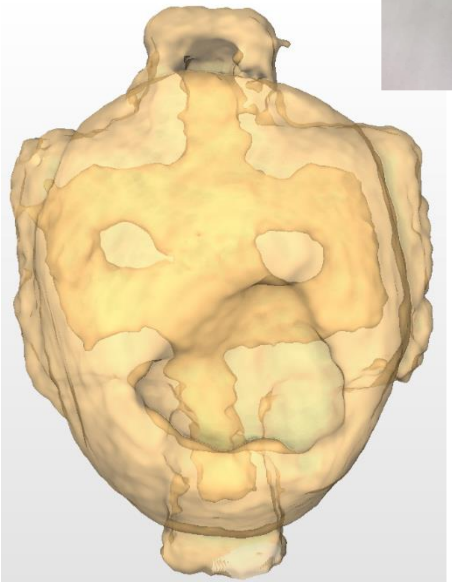
Spatial smoothness

$$||\nabla_S \mathbf{f}_t||_{\mathrm{H}_\epsilon}$$

Priors







Tomography

$$\|\mathbf{A}_t\mathbf{f}_t - \mathbf{p}_t\|_2^2$$

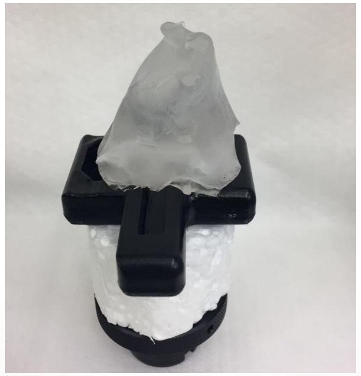
Spatial smoothness

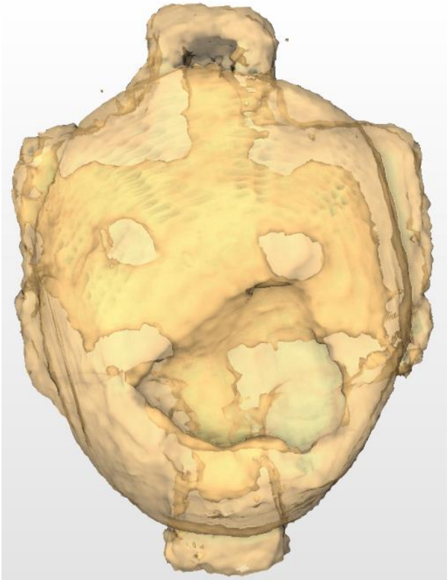
$$\|\nabla_S \mathbf{f}_t\|_{\mathrm{H}_\epsilon}$$

Temporal smoothness

$$\|\nabla_T \mathbf{f}_t\|_2^2$$

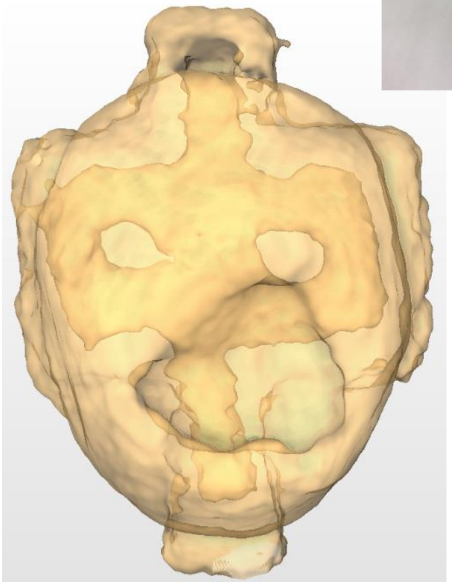
Priors





Tomography

$$\|\mathbf{A}_t\mathbf{f}_t - \mathbf{p}_t\|_2^2$$

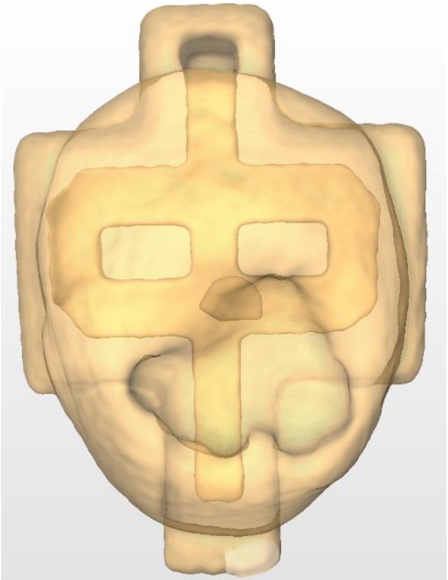


Spatial smoothness

$$\|\nabla_S \mathbf{f}_t\|_{\mathrm{H}_\epsilon}$$

Temporal smoothness

$$\|\nabla_T \mathbf{f}_t\|_2^2$$

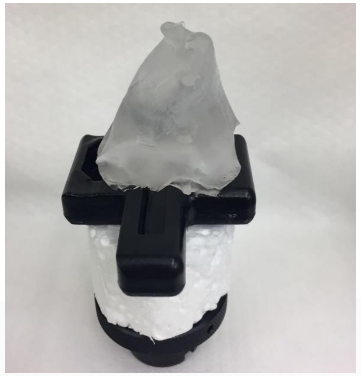


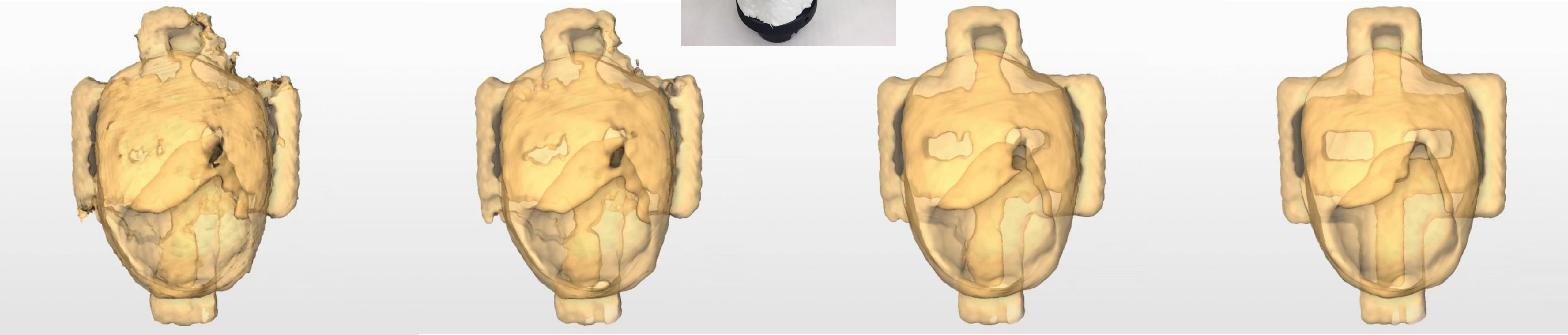
Flow correction

$$\|\nabla_T \mathbf{f}_t + \nabla_S \mathbf{f}_t \cdot \mathbf{u}_t\|_1$$

$$\sum_{i=x,y,z} \|\nabla_S \mathbf{u}_{t,i}\|_{\mathrm{H}_\tau}$$

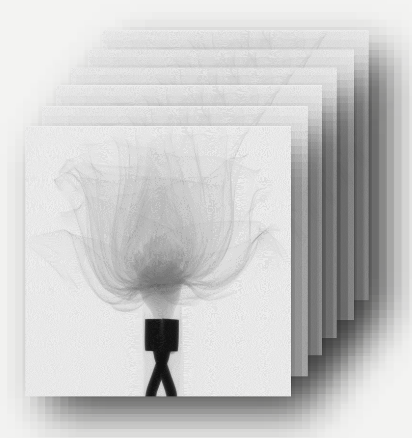
Priors





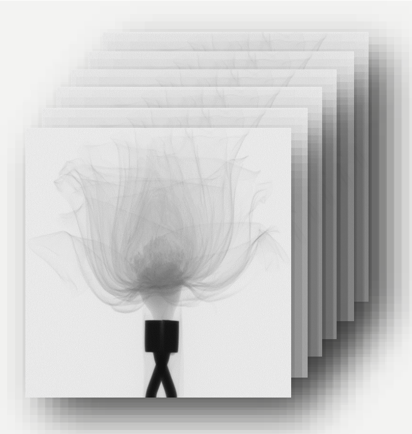
Tomography	Spatial smoothness	Temporal smoothness	Flow correction
$\|\mathbf{A}_t\mathbf{f}_t - \mathbf{p}_t\|_2^2$	$\|\nabla_S \mathbf{f}_t\|_{\mathrm{H}_\epsilon}$	$\|\nabla_T \mathbf{f}_t\|_2^2$	$\|\nabla_T\mathbf{f}_t + \nabla_S\mathbf{f}_t \cdot \mathbf{u}_t\|_1$ $\sum_{i=x,y,z} \|\nabla_S \mathbf{u}_{t,i}\|_{\mathrm{H}_\tau}$

4D joint optimization



Input

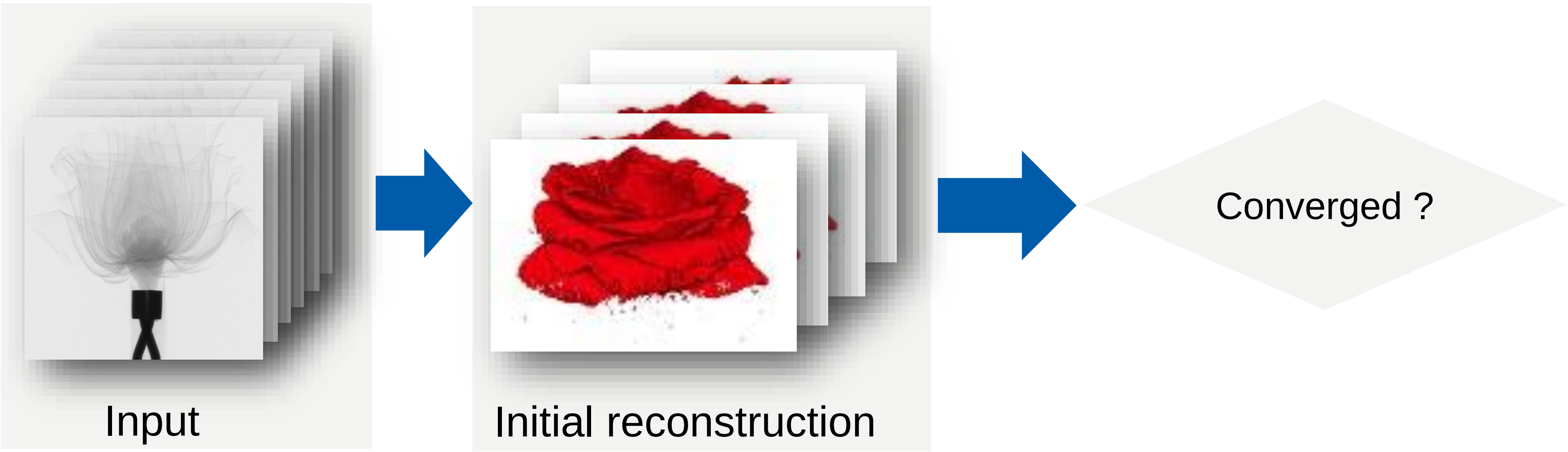
4D joint optimization



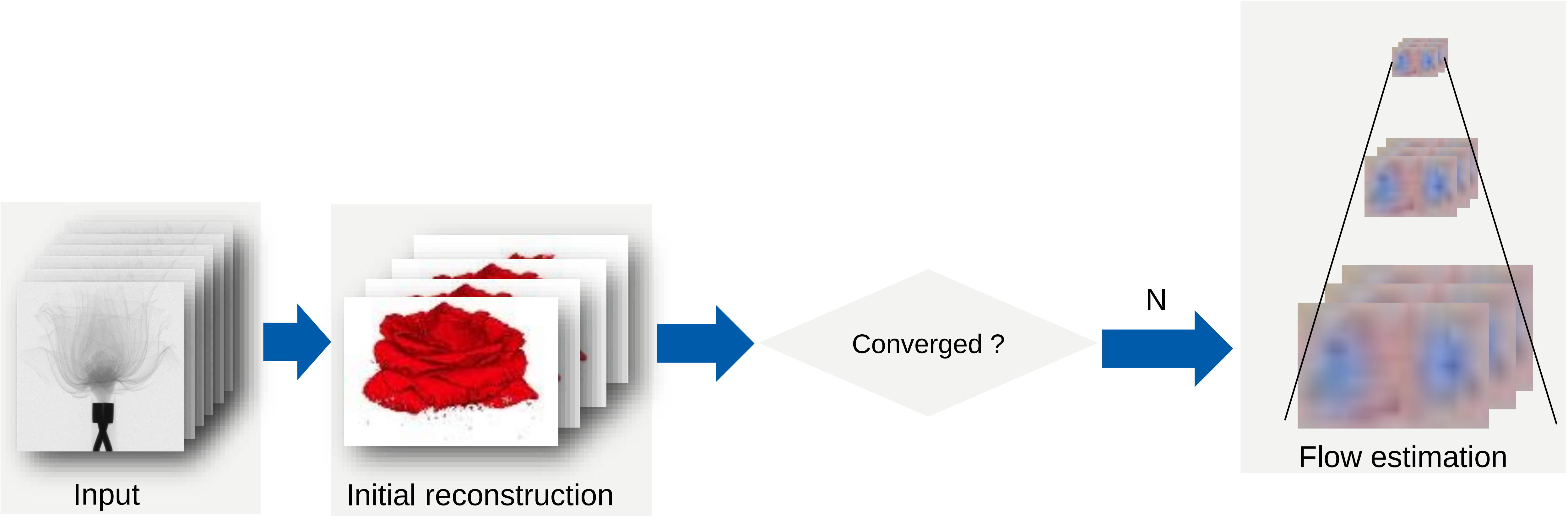
Input

Initial reconstruction

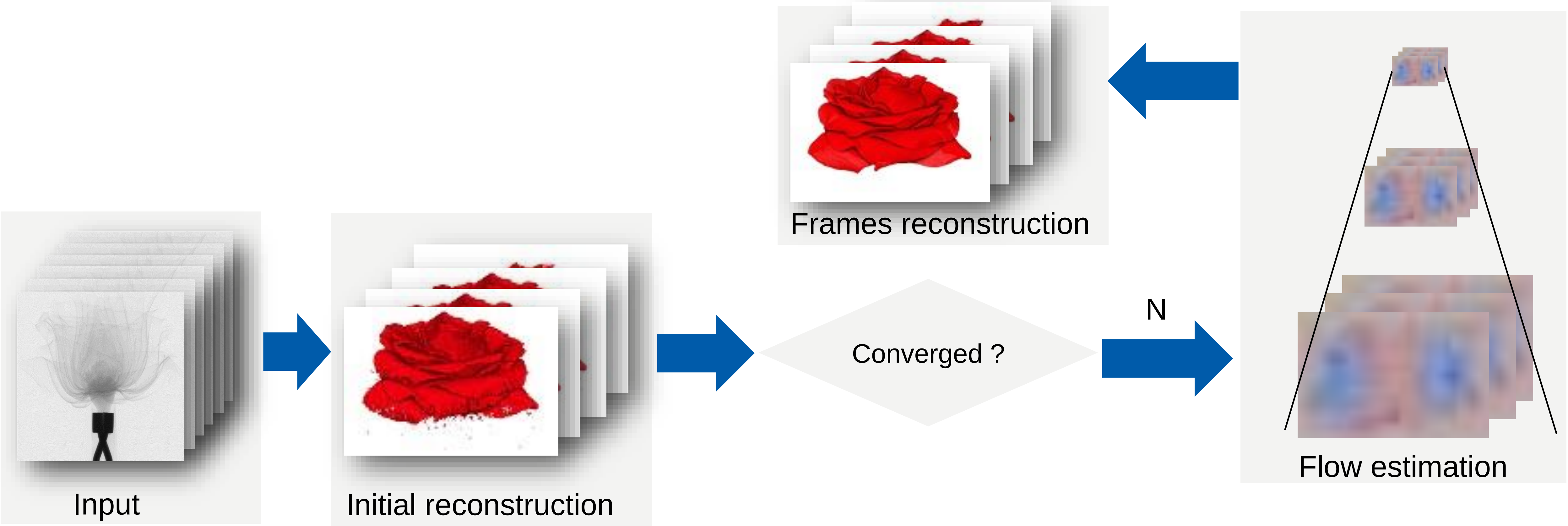
4D joint optimization



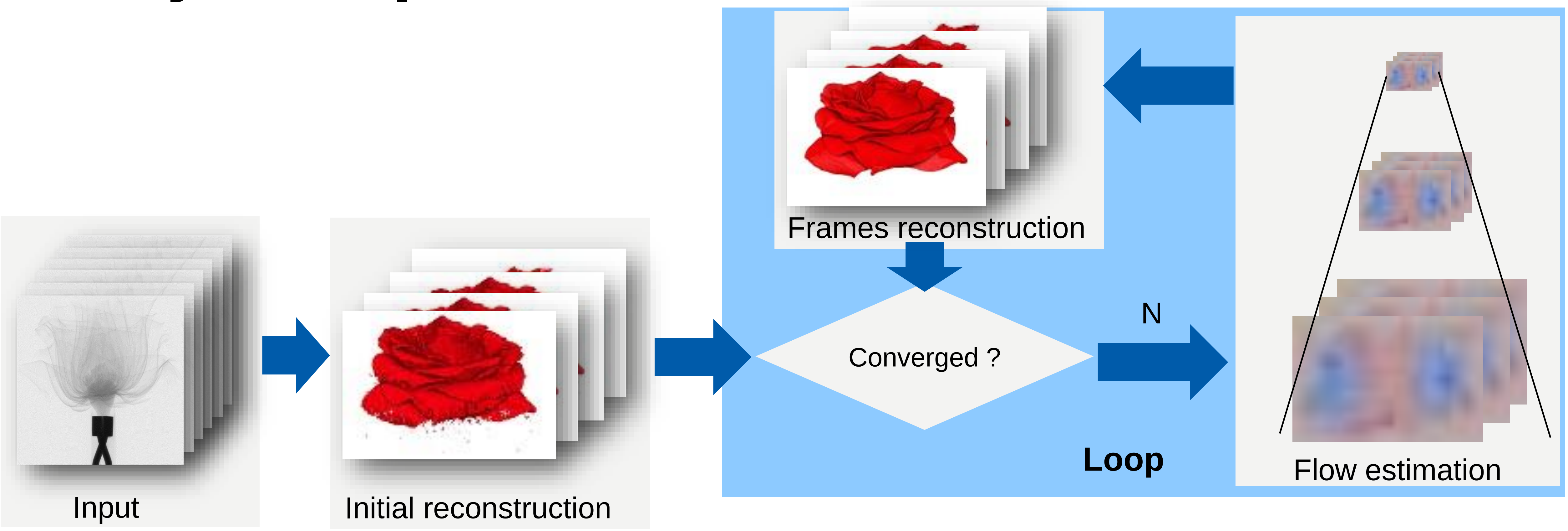
4D joint optimization



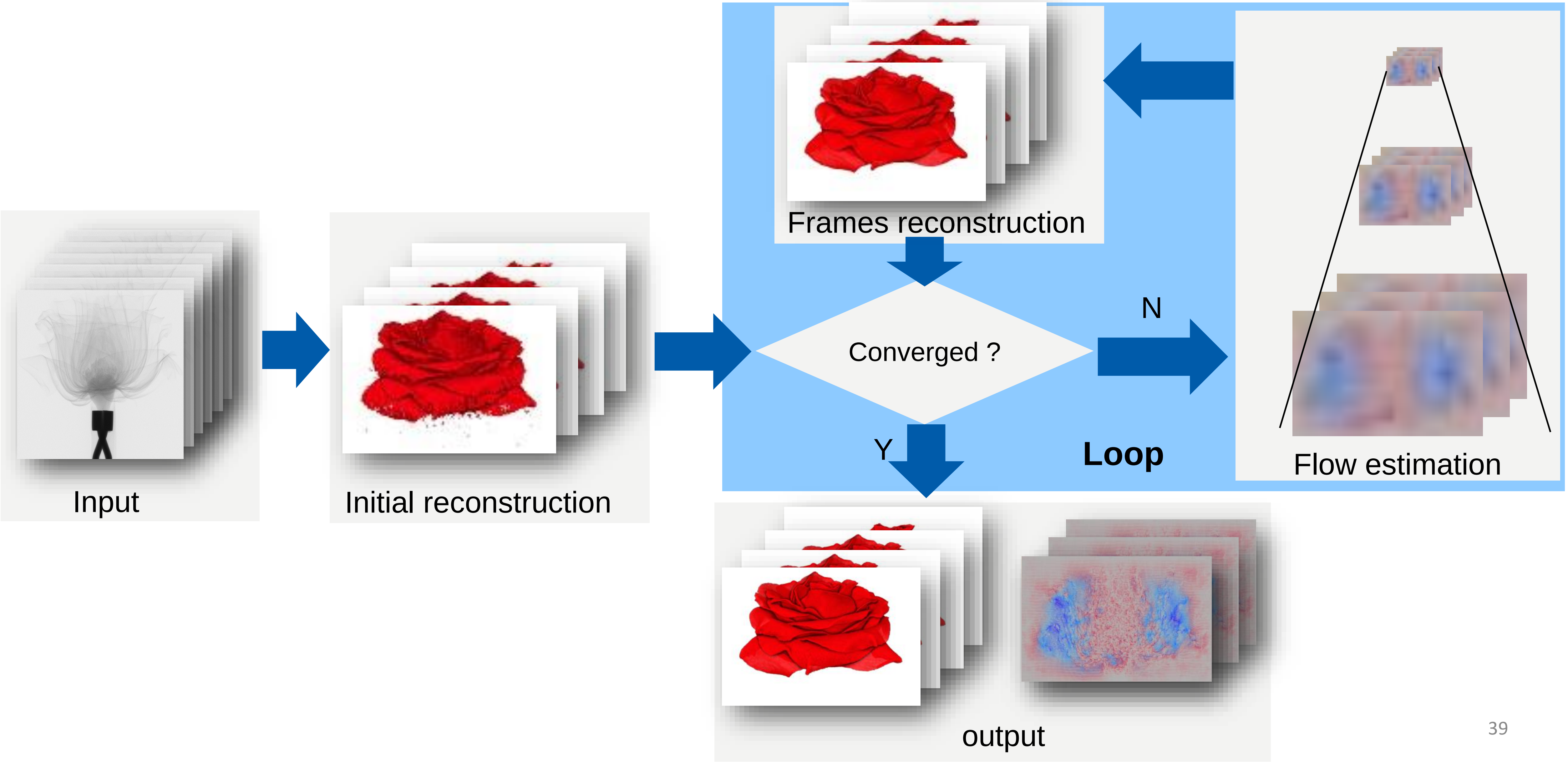
4D joint optimization



4D joint optimization



4D joint optimization



Overview

- Data acquisition
- 4D tomographic reconstruction
- Results

Wilting rose

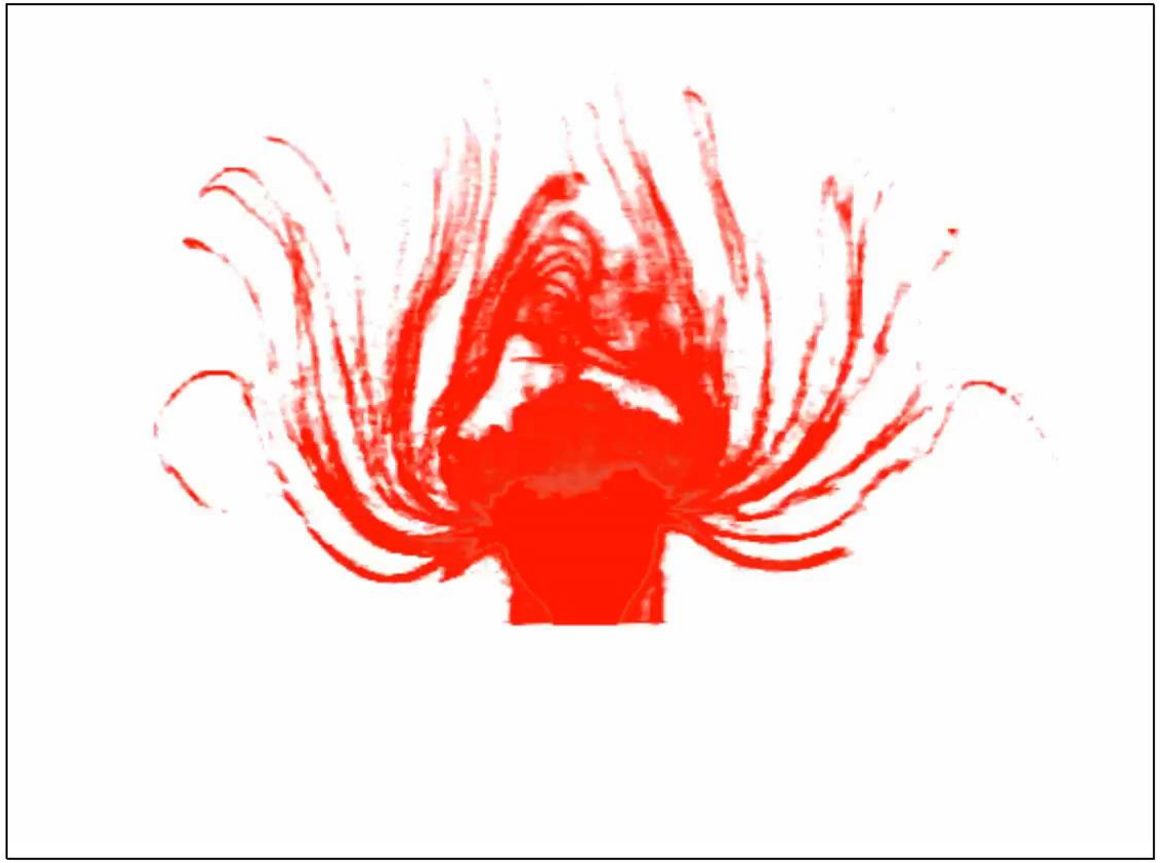
	Photo	Projection
Before		
After		

Wilting rose

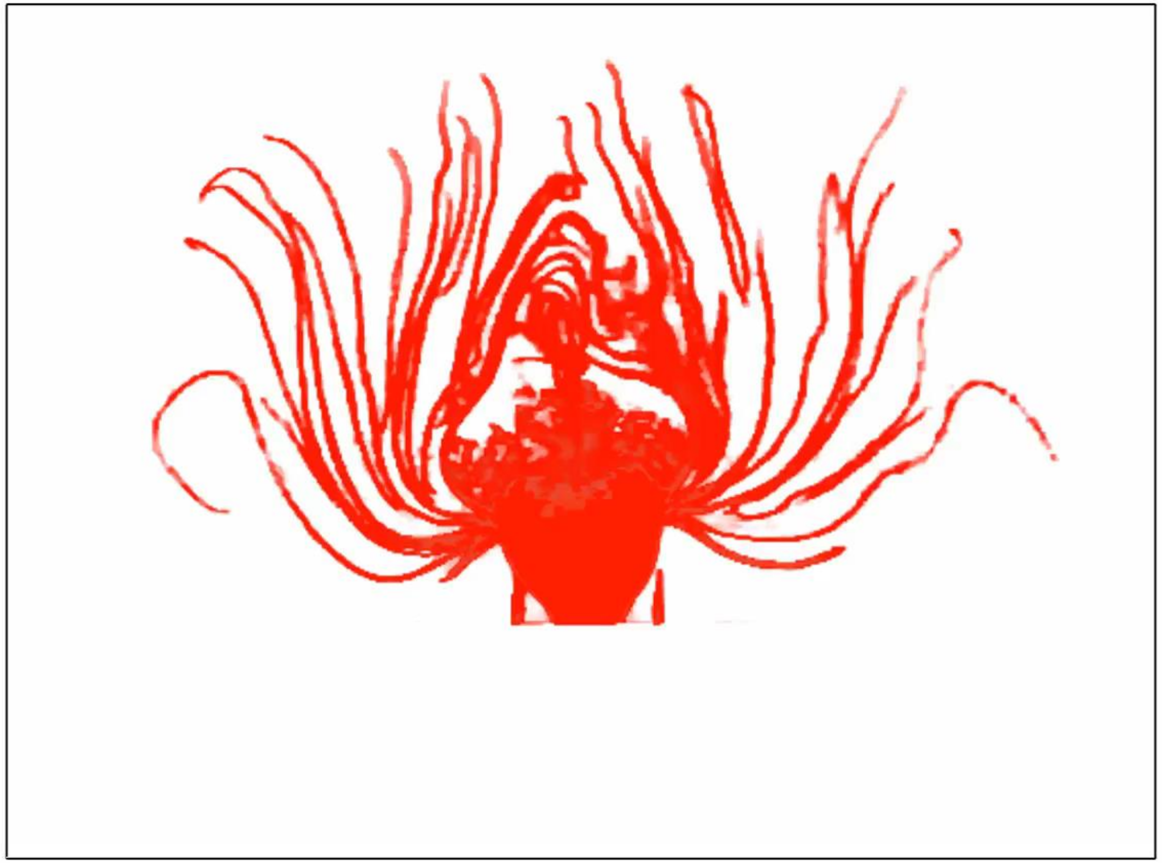
Baseline method

Ours

Wilting rose

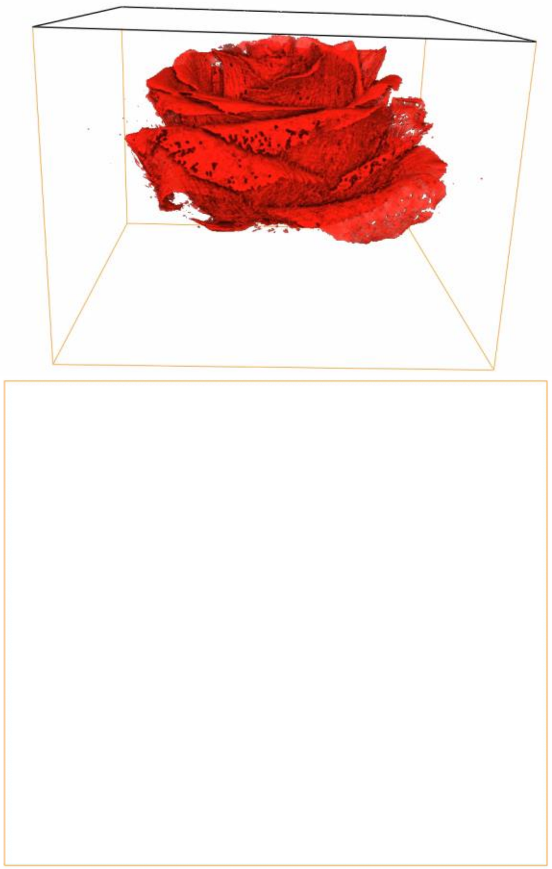


Baseline method

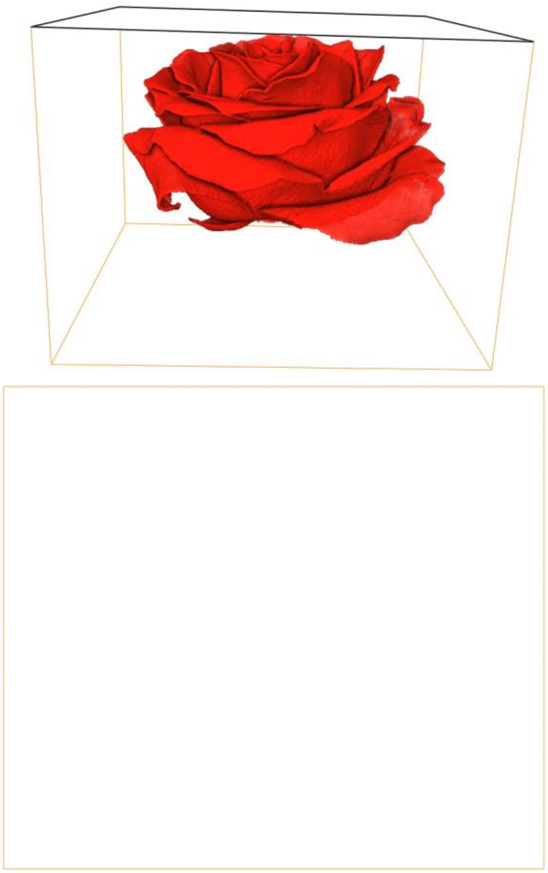


Ours

Wilting rose



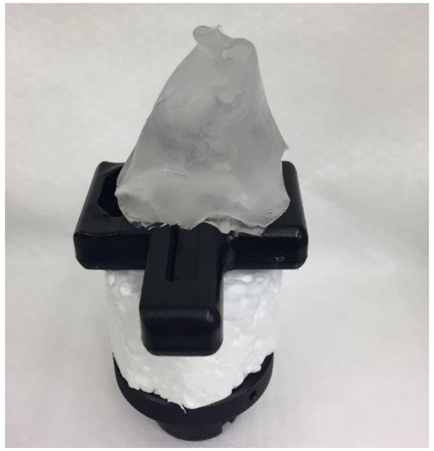
Baseline method

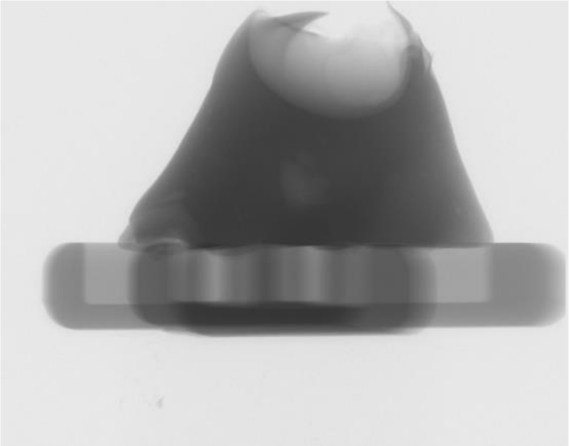


Ours

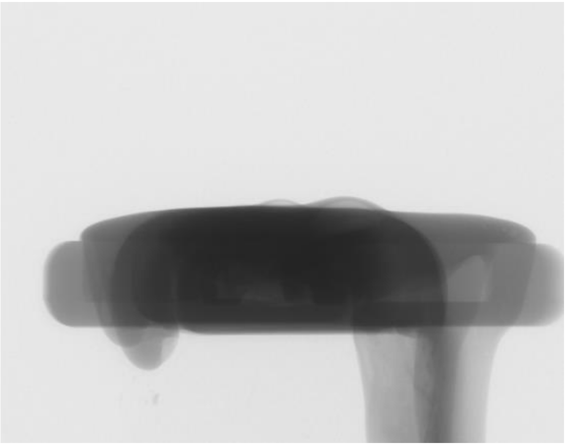
High viscosity fluid flow

Before





After

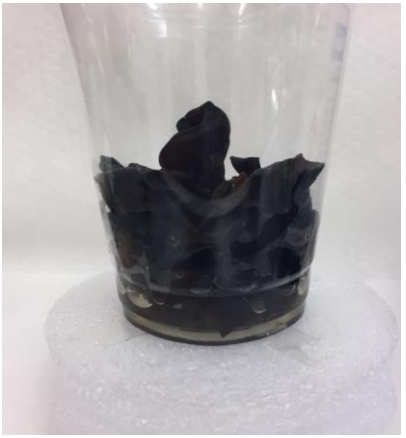


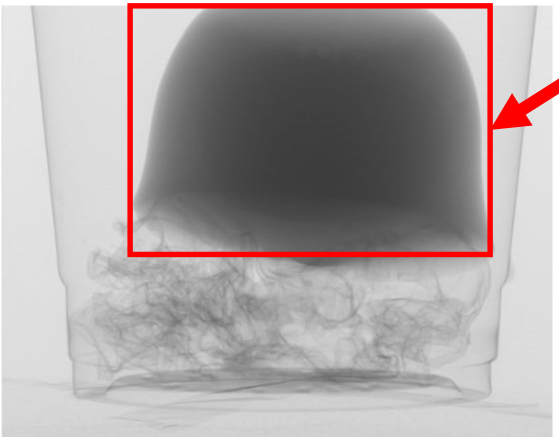
High viscosity fluid flow

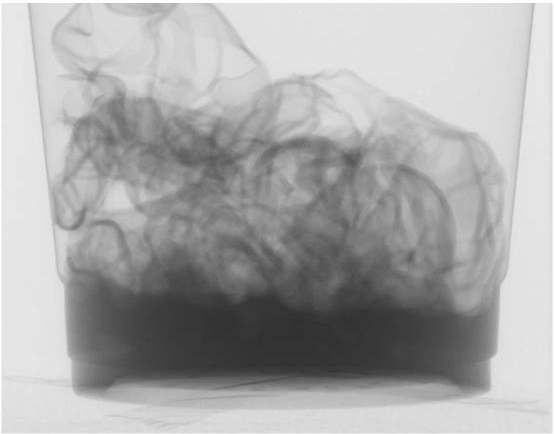
جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

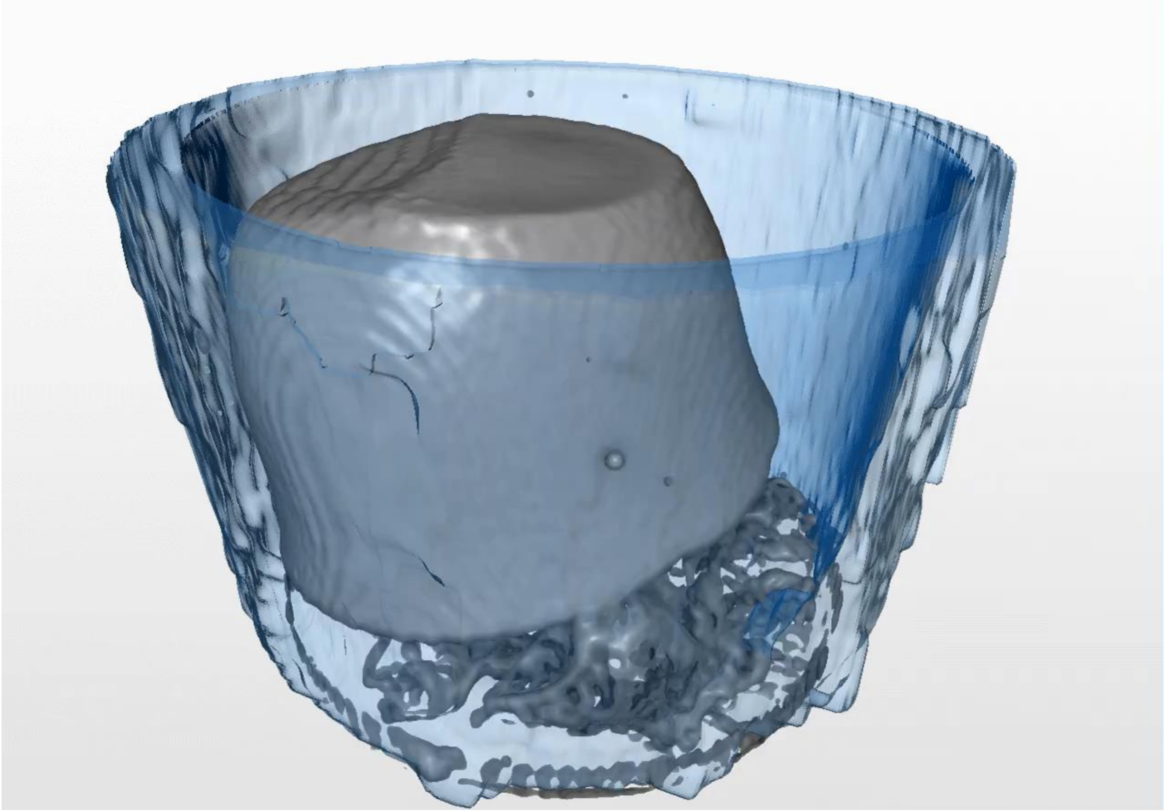
Mushroom re-hydration

Melting ice

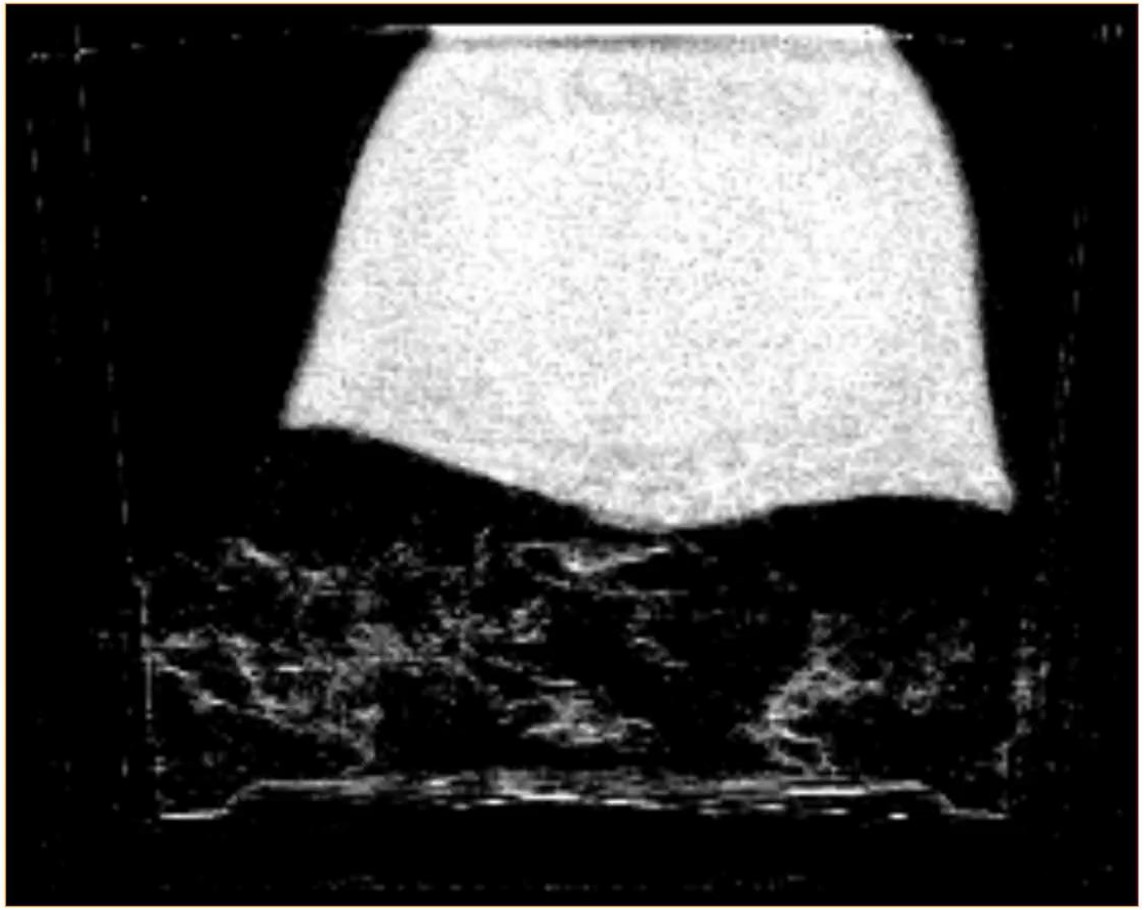








Mushroom re-hydration



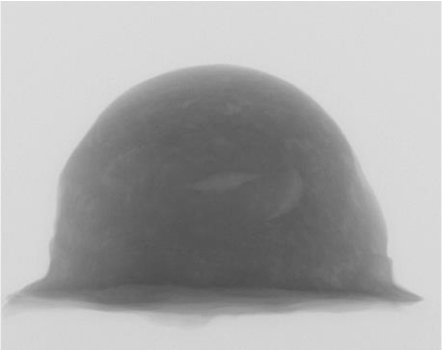
Baseline method

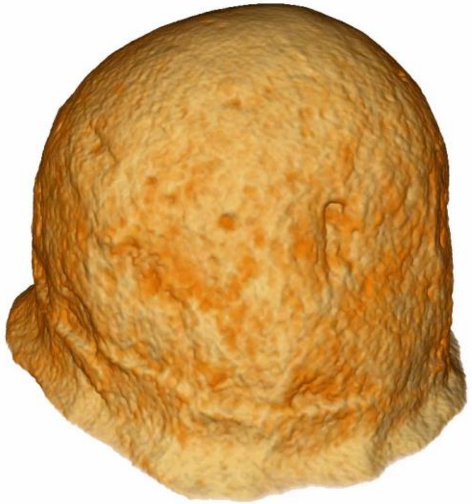
Ours

Mushroom re-hydration

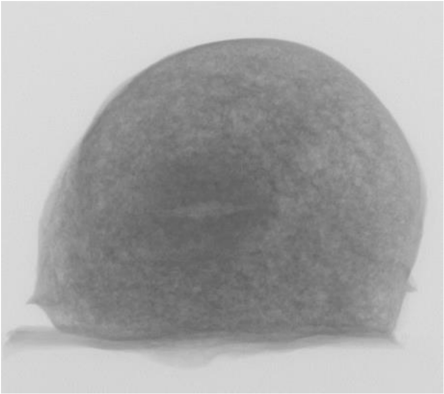
Rising dough

Before

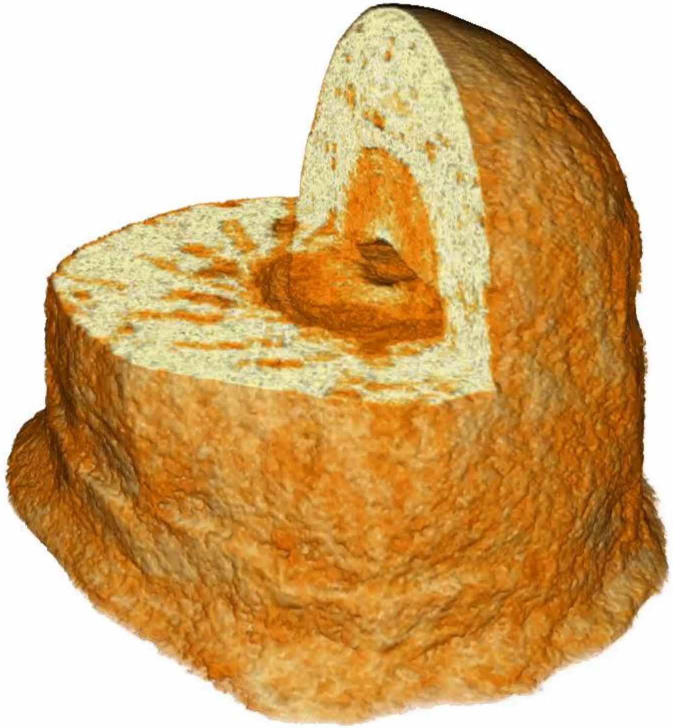




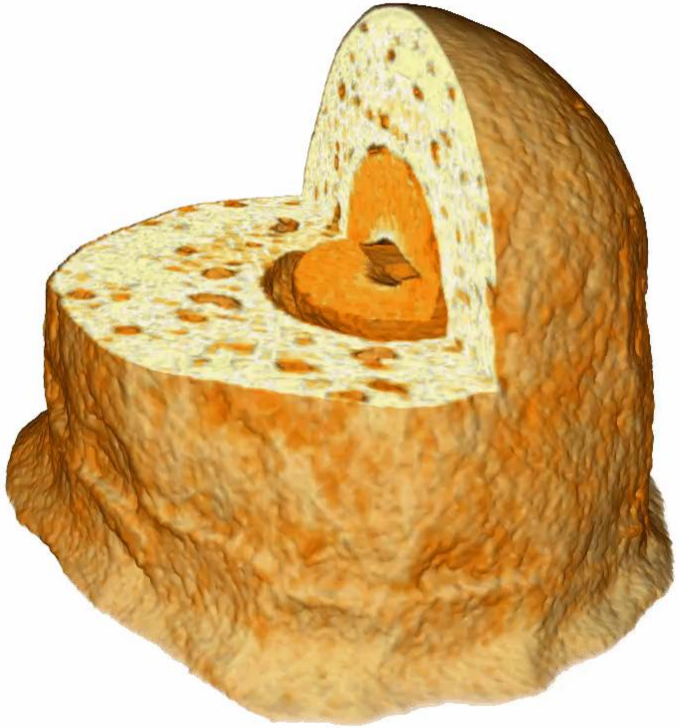
After



Rising dough

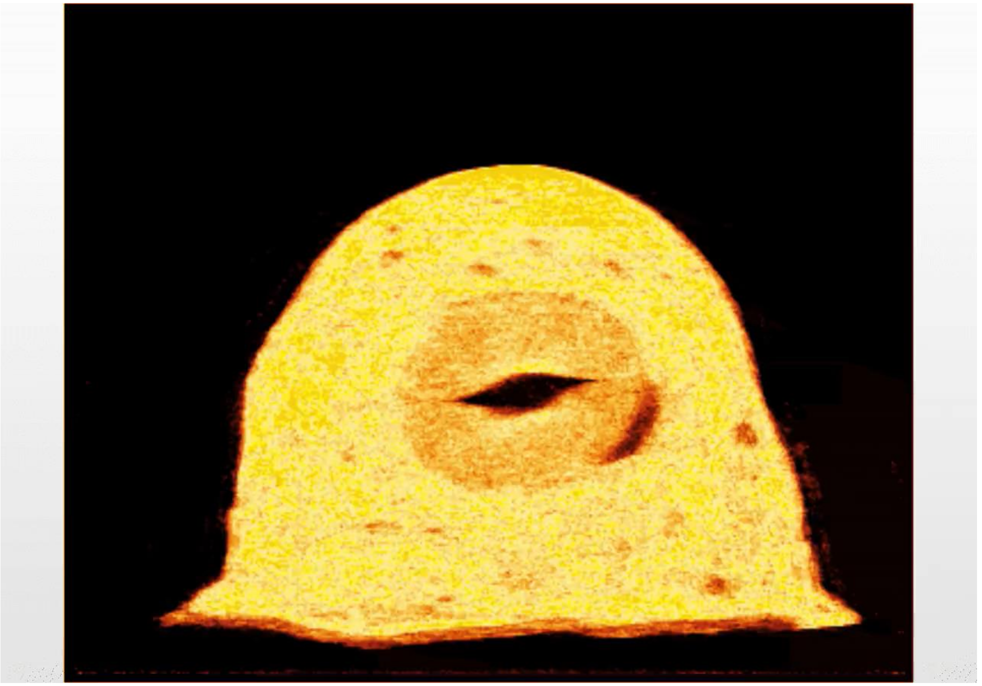


Baseline method

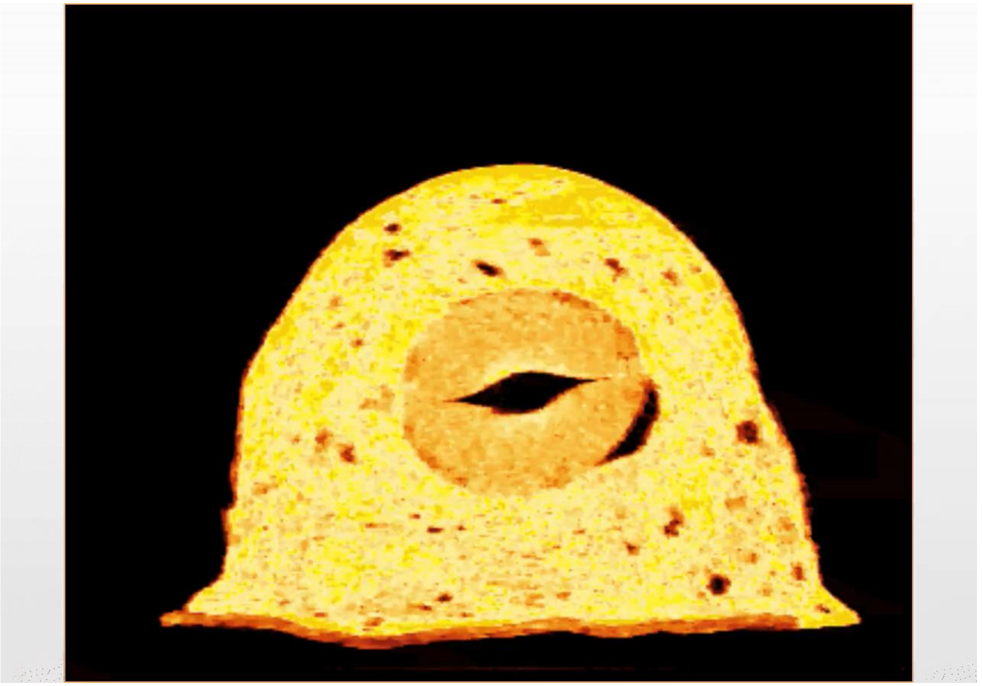


Ours

Rising dough



Baseline method

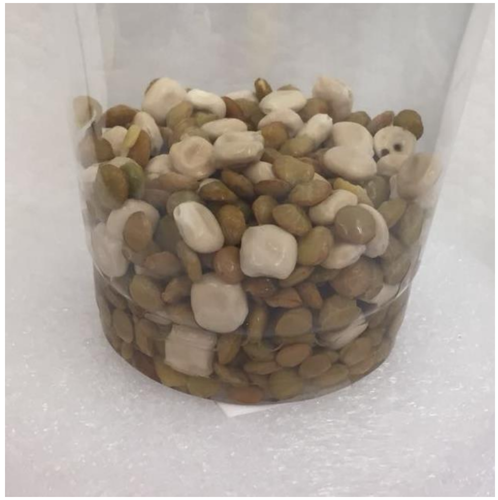


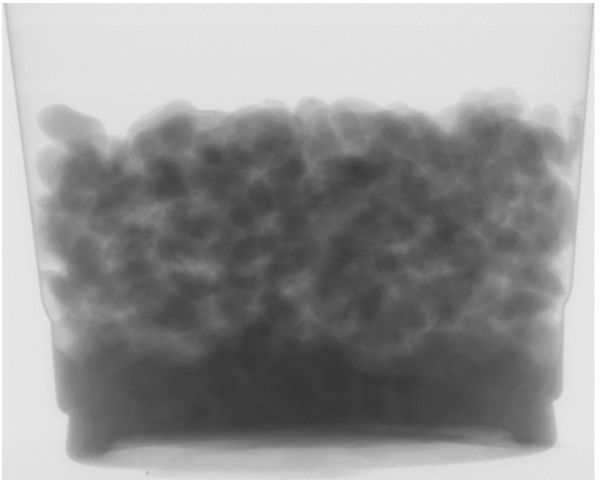
Ours

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

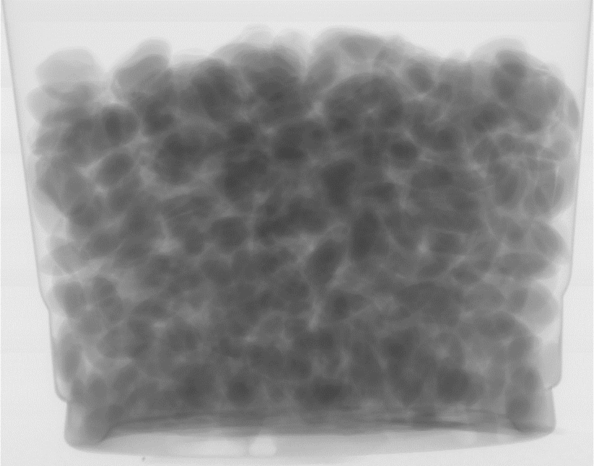
Lentil/lupin seeds hydration

Before

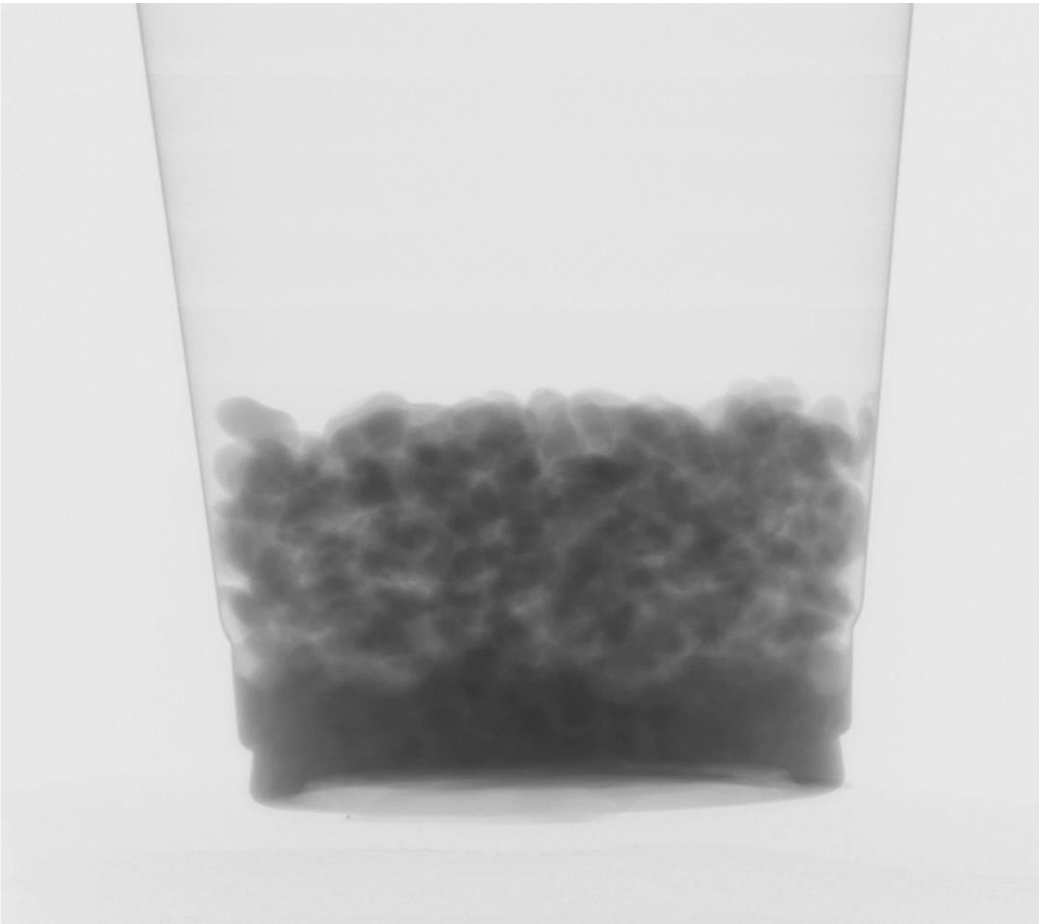




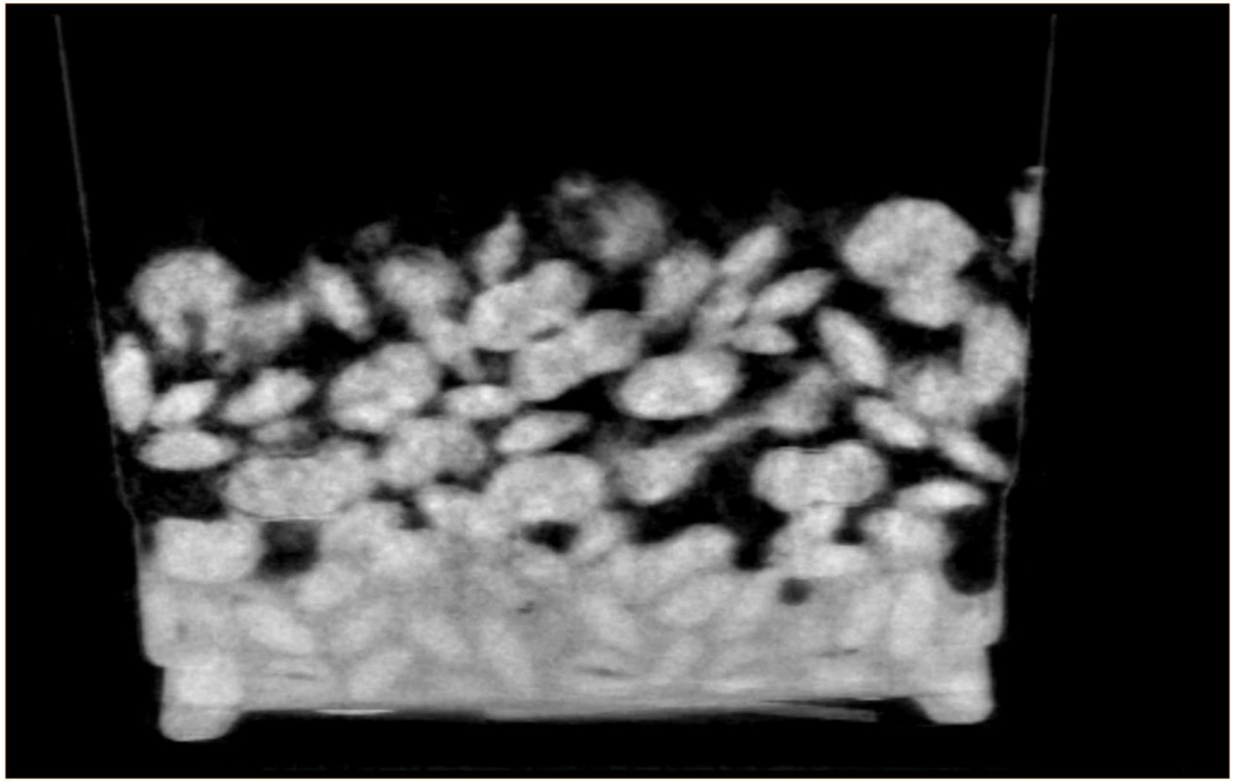
After



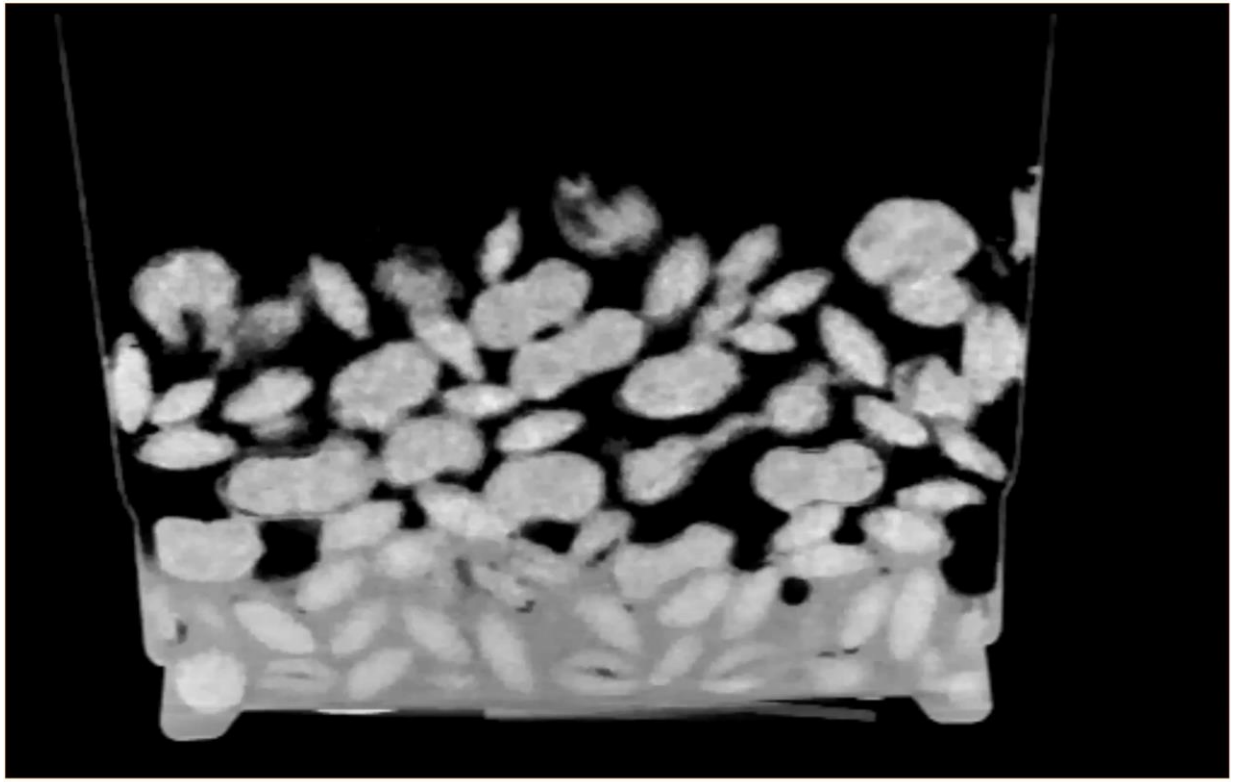
Lentil/lupin seeds hydration



Lentil/lupin seeds hydration



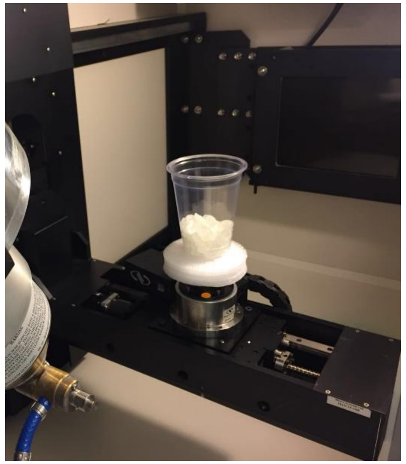
Baseline method

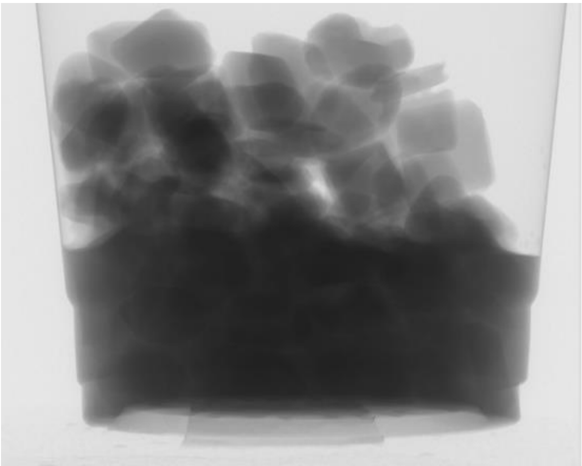


Ours

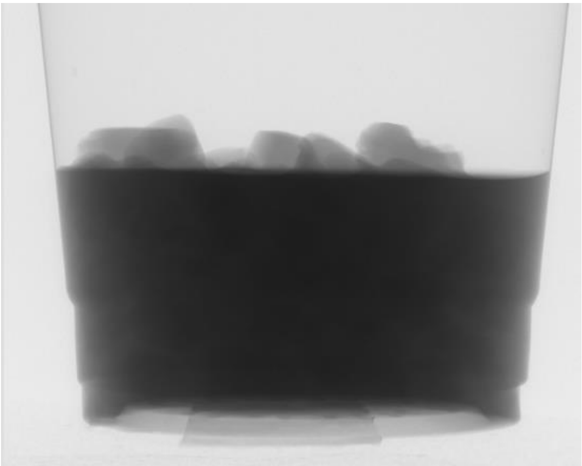
Crystal sugar dissolution

Before

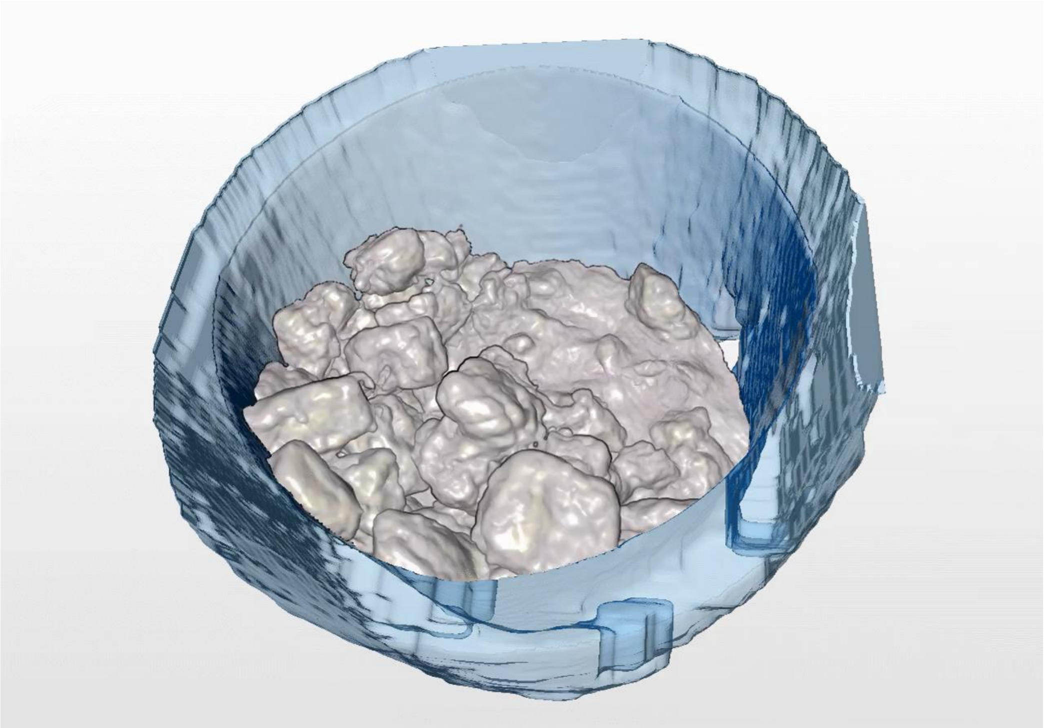


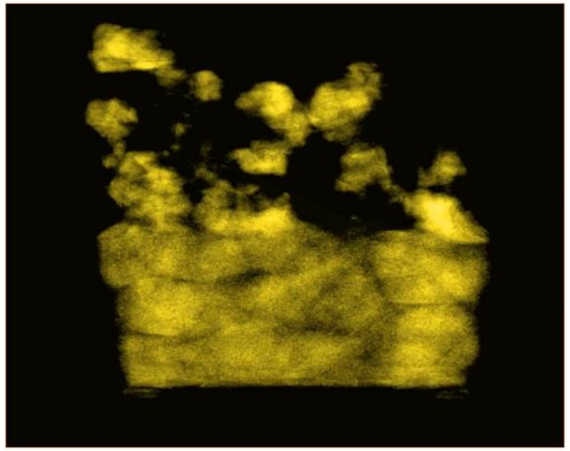


After

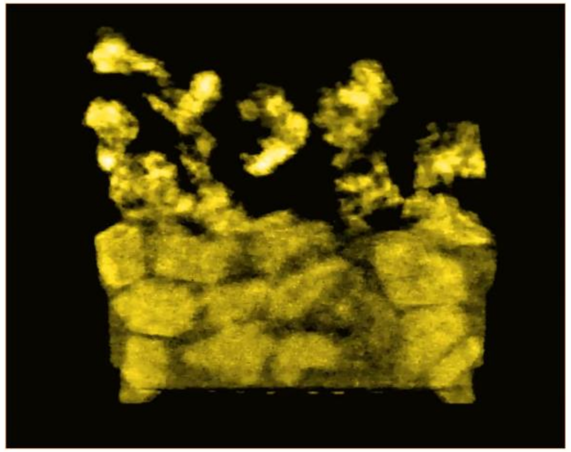


Crystal sugar dissolution





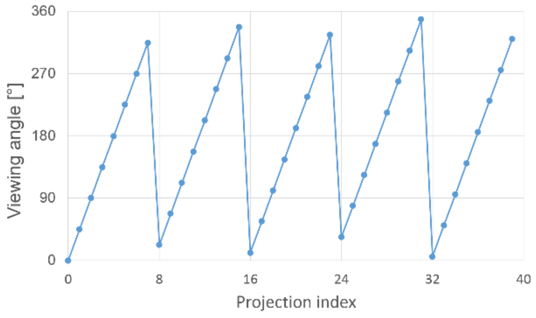
Baseline method



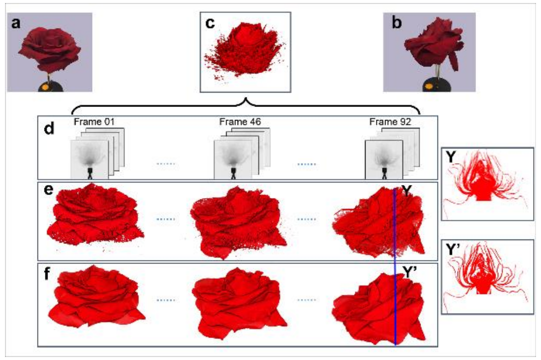
Ours

Summary

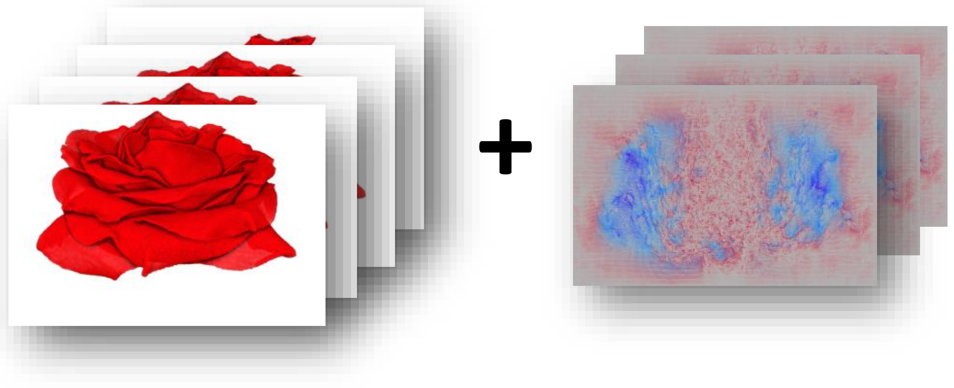
- A new sampling strategy



- A new 4D framework for tomography



- Well suited to graphics



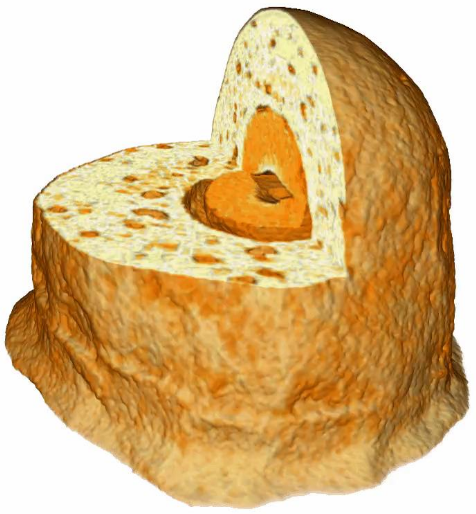
Next steps

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

- Extension to faster deformation
- Extension to other imaging modalities (e.g. electron microscope)
- Re-Simulation (e.g. domain modification)

Thank you !

Code & Data



Sponsorship: KAUST as part of VCC Center Competitive Funding.