Centrum Wiskunde & Informatica

Quasi-3D Iterative Reconstruction

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Overview

- Real-time tomography (introduction)
- Quasi-3D reconstruction
- Results
- Iterative slice reconstruction
- Conclusion

Real-time Tomography

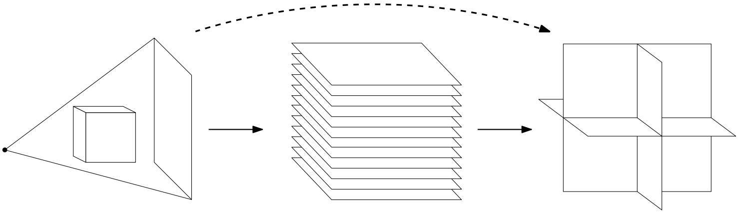
- Live reconstruction would allow us to look inside of an object during a tomographic scan.
- This is very useful for imaging experiments:
  - Observing dynamic processes inside the sample (while they are happening).
  - Controlling external parameters.
  - Adjust acquisition parameters.
- As fast as the slowest link: *acquisition*, *tomographic reconstruction*, *and visualization*.

Live reconstruction challenges

- Even with computationally efficient methods and implementations, the conventional reconstruction of 2000^3 voxel volumes takes minutes.
- By moving to distributed implementations, i.e. using multiple compute nodes, this can be reduced, but in general tomographic reconstruction seems hard to scale.
- Reconstructing full-resolution 3D volumes, for arbitrary acquisition geometries, in less than a second seems infeasible.

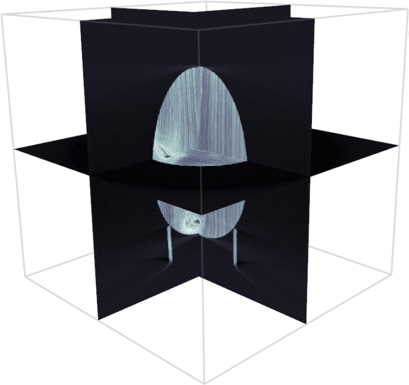
Real-time visualization

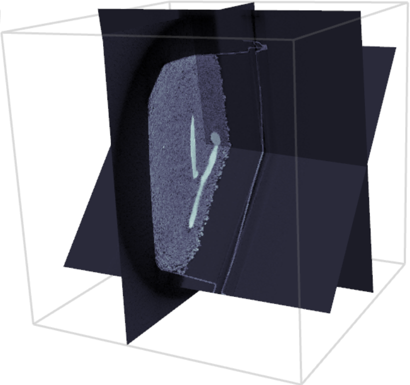
- 3D volumes often still visualized with slices: why not reconstruct individual slices directly?
- Maintain an illusion of having live 3D reconstructions
  - Arbitrarily oriented 2D slices.
  - Low resolution 3D preview.
- Make it easy to change the visualized slices on the fly.



- We call this *quasi-3D reconstruction*.

Visualization example





FBP-type algorithms

- How can we reconstruct slices directly?
- We write the tomographic reconstruction problem as $Ax = b$, components of x are voxels, components of b are (detector) pixels.
- Filter-then-backproject algorithms such as FBP, FDK and Katsevich's algorithm can be written as:

$$x^{\text{recon}} = A^T F b.$$

- Note that every component x_i of x^{recon} is reconstructed independently, using only the ith column of A.

$$\begin{bmatrix} \vdots \\ x_i \\ \vdots \end{bmatrix} = \begin{bmatrix} \cdots & a_i & \cdots \end{bmatrix}^T (Fb) \quad \Rightarrow \quad x_i = a_i^T (Fb).$$

FBP-type algorithms (cont.)

- Reconstructing an arbitrarily oriented slice can be written as:

$$\left[\frac{x_{\text{slice}}}{x_{\text{other}}}\right] = \left[\begin{array}{c|c} A_{\text{slice}} & A_{\text{other}} \end{array}\right]^T (Fb) \quad \Rightarrow \quad x_{\text{slice}} = A_{\text{slice}}^T (Fb).$$

- Since a slice can be seen as a 3D volume with a thickness of a single voxel, A_{slice} can be generated efficiently and independently.[1]

[1] *Real-time quasi-3D tomographic reconstruction*. JW Buurlage, H Kohr, WJ Palenstijn, KJ Batenburg. MST (2018).

Results

Runtime of reconstructions

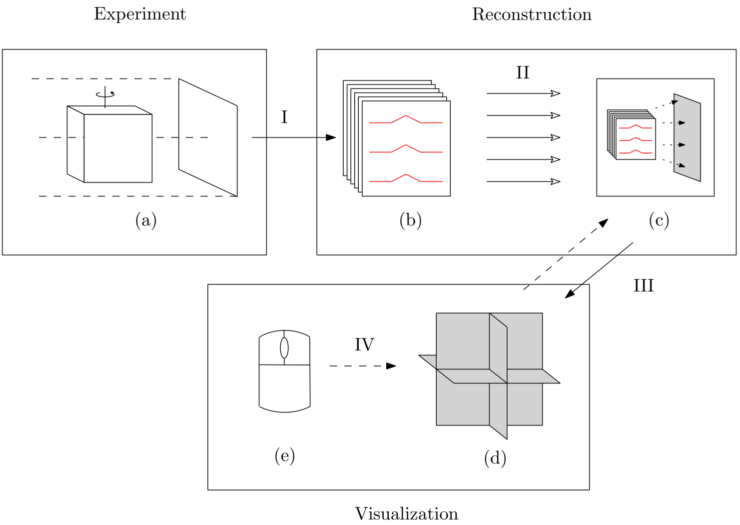
voxels	GPUs	full 3D	axial	vertical	tilted
$256 \times 256 \times 256$	$1\times$	0.84 s	26.5 ms	22.6 ms	23.8 ms
	$4\times$	0.31 s	35.9 ms	26.6 ms	22.9 ms
$512 \times 512 \times 512$	$1\times$	1.07 s	33.4 ms	22.6 ms	31.8 ms
	$4\times$	0.60 s	40.4 ms	27.2 ms	23.5 ms
$1024 \times 1024 \times 1024$	$1\times$	17.3 s	61.6 ms	64.8 ms	63.1 ms
	$4\times$	6.69 s	38.5 ms	39.1 ms	37.2 ms
$2048 \times 2048 \times 1024$	$1\times$	274 s	286 ms	5.22 s	5.48 s
	$4\times$	65.0 s	100 ms	106 ms	105 ms

Live reconstruction experiments @ TOMCAT

- TOMCAT beamline at the Swiss Light Source at PSI, ultra-fast tomographic imaging of dynamic processes.
- GigaFRoST is a system for ultra-fast detection and readout for tomographic microscopy.
- RECAST3D: 3D slice reconstruction and visualization built on top of a message-passing protocol between the different stages: acquisition, reconstruction and the visualizer.
- Together, these components allow for real-time visualization of dynamic processes.[2]

[2] Ongoing collaboration with Federica Marone and Christian Schlepütz

Overview message-passing protocol



[Video]

[Video]

Quasi-3D summary

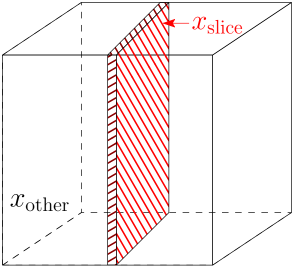
- We introduce real-time quasi-3D tomographic reconstruction, and have developed RECAST3D which is based on this idea.
- Reconstructing a limited number of arbitrarily oriented slices can be done at a fraction of the computational cost of a full 3D reconstruction.
- Being able to visualize multiple arbitrarily oriented slices can yield sufficient information and insight for many use cases.

Iterative slice reconstruction

Slice reconstructions

- Our quasi-3D framework is a viable way to realize real-time reconstruction and visualization, however…
- For ultra-fast experiments, typical for dynamic imaging, data is usually sparse and noisy. FBP performs poorly under these constraints.
- Iterative algorithms generally perform better in this situation, and furthermore allow for incorporating a priori information, regularization, and so on.

Iterative slice reconstruction



$$\begin{bmatrix} A_{\text{slice}} & A_{\text{other}} \end{bmatrix} \begin{bmatrix} x_{\text{slice}} \\ x_{\text{other}} \end{bmatrix} = b \quad \Longrightarrow \quad A_{\text{slice}} \underbrace{x_{\text{slice}}}_{1} = \underbrace{b}_{2} - \underbrace{A_{\text{other}} x_{\text{other}}}_{3}$$

1. Slice reconstruction
2. Measurements
3. Outside influence

Approximating the outside influence

$$A_{\text{slice}} \underbrace{x_{\text{slice}}}_{1} = \underbrace{b}_{2} - \underbrace{A_{\text{other}} x_{\text{other}}}_{3} \equiv \tilde{b}$$

- If we can approximate $A_{\text{other}} x_{\text{other}}$ accurately, then we obtain a 'standard' reconstruction problem.
- *Note*: we do not care about the reconstruction quality of x_{other}, only about the accuracy of $A_{\text{other}} x_{\text{other}}$.
- An arbitrary slice can be seen as a particularly challenging region of interest.

FBP

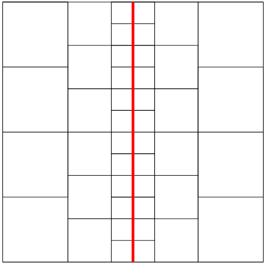
- FBP: Reconstruct the image with FBP at low resolution

$$x_{\text{other}} = M_{\text{slice}} A_{\text{low-res}}^{T} F b.$$

- Straightforward implementation, and computationally efficient.
- A combination of FBP with iterative reconstruction for e.g. ROI tomography has been studied before by Ziegler et al. (2008), De Witte et al. (2010) and Kopp et al. (2015).

Multi-grid

- Multi-grid: Let the resolution depend on the distance to the slice. Simultaneously reconstruct the outside and the slice.



- Succesfully applied to ROI reconstruction, see e.g. Hamelin (2010).

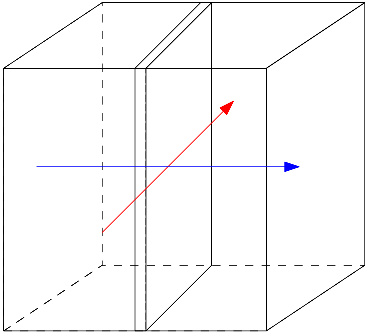
SVD

- Truncated SVD:

$$x \approx V_k \Sigma_k^{-1} U_k^T b.$$

- Randomized algorithms can approximate the SVD, analytic solution known for standard geometries.
- The idea is to ignore high-frequency information outside the slice, similar to the ROI approach by e.g. Niinimäki et al. (2007).
- *Downsides:* computationally expensive, and memory intensive.

Geometric heuristic



- Ignore data corresponding to rays with a small angle of incidence, as they contain little information for the slice of interest.

Conclusion

Conclusion

- Live reconstruction has many interesting applications, and is a challenging computational problem.
- FBP-type algorithms are *local*, can reconstruct slices directly but can give suboptimal reconstruction quality.
- RECAST3D: real-time tomography reconstruction and visualization is available as open-source software.[3]
- Iterative reconstruction of individual slices desirable but not as easy to realize.

Thank you for your attention!

[3] http://github.com/cicwi/