Fast Deformation Imaging from Limited-Angle Projections in Radiation Therapy

Alexandros-Stavros Iliopoulos* Nikos P. Pitsianis* Xiaobai Sun* Fang-Fang Yin† Lei Ren†

*Department of Computer Science, Duke University †Department of Radiation Oncology, Duke University School of Medicine

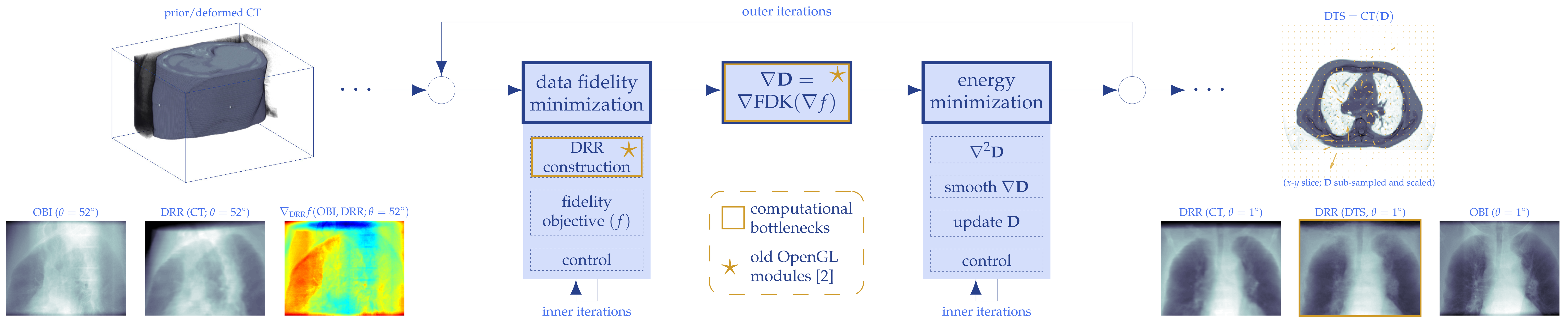
Introduction

Image-guided radiation therapy is a major paradigm in cancer treatment, where on-board images (OBIs) may be used to monitor tumor motion and adjust radiation delivery.

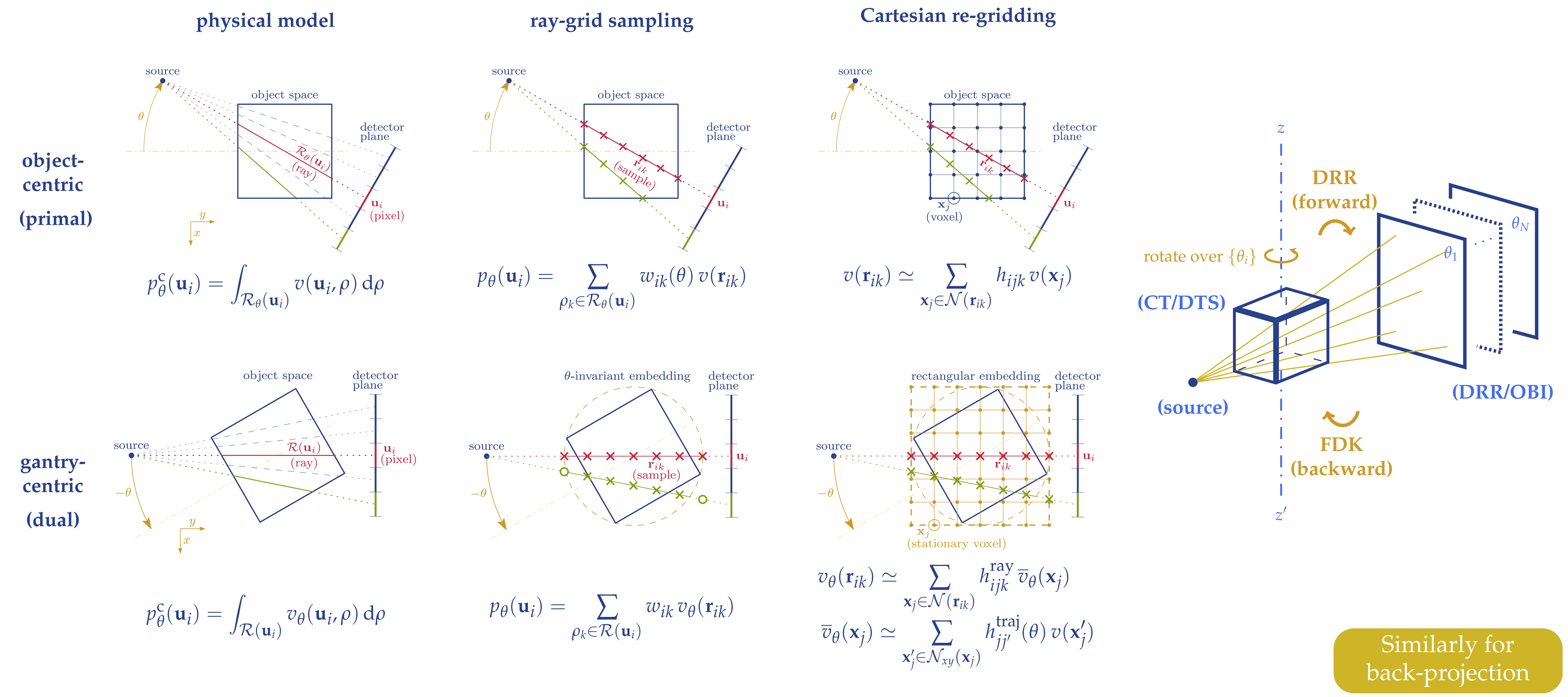
The LIVE system [1], developed at Duke University, may account for intrafraction motion via Digital Tomosynthesis (DTS) from a limited-angle OBI scan. This reduces imaging time and dose; however, DTS is performed through iterative deformable registration [3], which presents a challenge in meeting clinical response time requirements.

We propose a versatile model for the design and development of primitive operations for DTS. Its purpose is to facilitate (a) flexible composition and (b) high-performance numerical implementation of advanced DTS algorithms. We demonstrate our approach and its results for the case of LIVE.

Digital tomosynthesis reconstruction scheme [3]



Digital forward projection models: primal & dual



Advantages

- Composition of digital operator weights—e.g. for DRR generation:

$$\mathbf{p}_\theta \simeq \mathbf{C}(\theta)\,\mathbf{M}(\theta)\,\mathbf{v}, \qquad \text{or} \qquad \mathbf{p}_\theta \simeq \mathbf{C}_{\text{ray}}\,\mathbf{M}_{\text{ray}}\,\overline{\mathbf{v}}_\theta, \qquad \overline{\mathbf{v}}_\theta \simeq \left[\left(\mathbf{C}_{\text{traj}}(\theta)\,\mathbf{M}_{\text{traj}}(\theta)\right) \otimes \mathbf{I}_z\right] \mathbf{v}$$

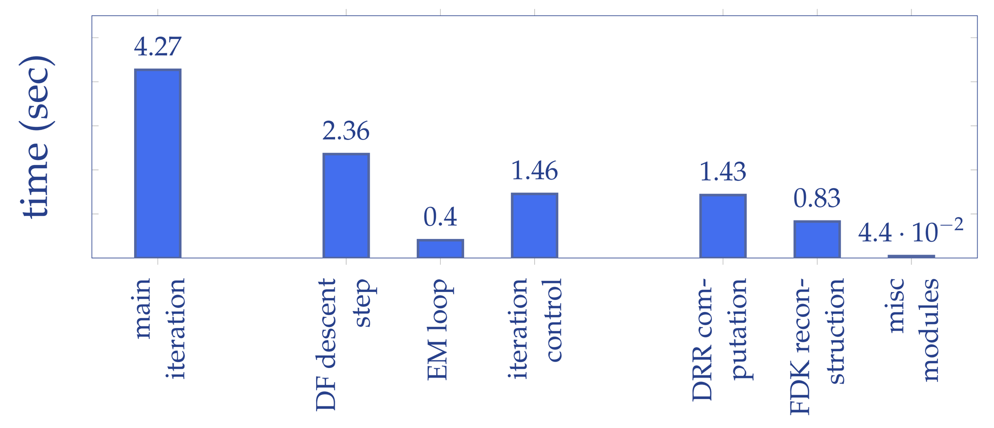
- Separation of static (geometric and numerical model) and dynamic (volume/detector data) processing:
  - **C** (composite coefficients) and **M** (grid masks) may be pre-computed
  - only **v** and $\mathbf{p}_\theta$ vary across iterations
- Reduced space (memory) and time (# of operations) complexity with dual model:

Set	Model configuration					Space (GiB)		Time (GFLOP)	
	Ω_v	Ω_p	$\lvert\Theta\rvert$	$\lvert\mathcal{R}(\mathbf{u})\rvert$	$\mathcal{N}(\mathbf{x})$	Primal	Dual	Primal	Dual
A	256×256×160	512×384	30	256	2×2×2	45.2	1.2	23.0	9.8
B	256×256×160	512×384	60	256	2×2×2	113.0	1.3	26.7	19.6
C	256×256×160	512×384	60	256	6×6×6	244.2	3.4	805.6	206.1
D	512×512×320	1024×768	60	512	2×2×2	903.8	10.0	213.4	157.0

space-time complexities refer to both forward and backward projection operators, assuming all static data are pre-computed

- Efficiency and versatility:
  - Numerical accuracy (discrete weights model) decoupled from performance
  - Flexible mapping to computing architecture
  - Composable coefficients ⟶ modular, high-level implementations
  - Modest memory overhead
  - (Almost) same complexities for helical and saddle source trajectories

Timing results



Total execution time (20 iterations):
- Previous: 1h 30m [2, 3]
- Current: **1m 25s** (60×)
- Target: < 2s (interactive)

Execution parameters:
- 3D volume (CT/DTS): 256 × 256 × 136
- 2D projections (OBI/DRR): 512 × 384
- # of projection angles: 62
- AMD Opteron 6168 & NVIDIA Tesla K20c

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Key references

[1] L. Ren, Y. Zhang, and F.-F. Yin. A limited-angle intrafraction verification (LIVE) system for radiation therapy. *Medical Physics*, 41(2):020701, Feb. 2014.

[2] H. Yan, L. Ren, D. J. Godfrey, and F.-F. Yin. Accelerating reconstruction of reference digital tomosynthesis using graphics hardware. *Medical Physics*, 34(10):3768, Oct. 2007.

[3] Y. Zhang, F.-F. Yin, W. P. Segars, and L. Ren. A technique for estimating 4D-CBCT using prior knowledge and limited-angle projections. *Medical Physics*, 40(12):121701, Nov. 2013.

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