

Rapid Projection Computations for On-board Digital Tomosynthesis in Radiation Therapy

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Disclosure

This work has been supported by:

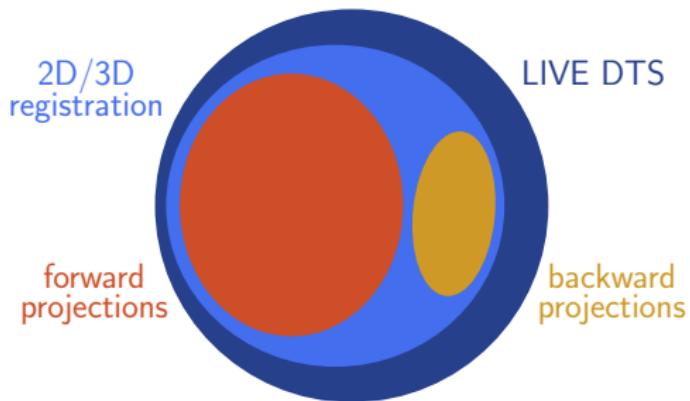
- NIH, grant #R01-CA184173
- ARO, grant #W911NF-13-I-0344
- NVIDIA Corporation, K40 GPU donation

An extended, slightly different version has been presented at GTC-2015

Introduction: on-board deformable registration

- LIVE: limited-angle, on-board intrafraction target verification^{1,2}
 - fast, low-dose acquisition — computational challenge
- planning volume (3D) $\xleftrightarrow{\text{deform}}$ on-board projection images (2D)
 - iterative 2D/3D deformable registration

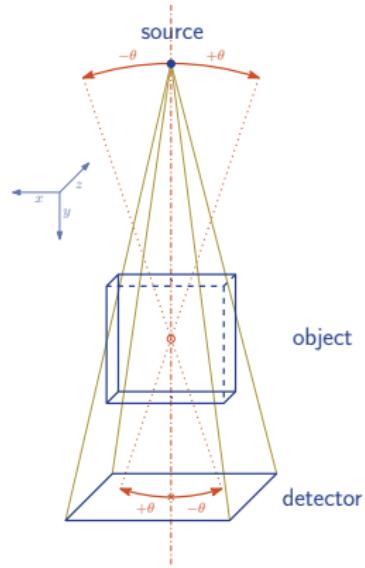
- bottleneck: projections



¹Zhang et al, *Med Phys*, 2013

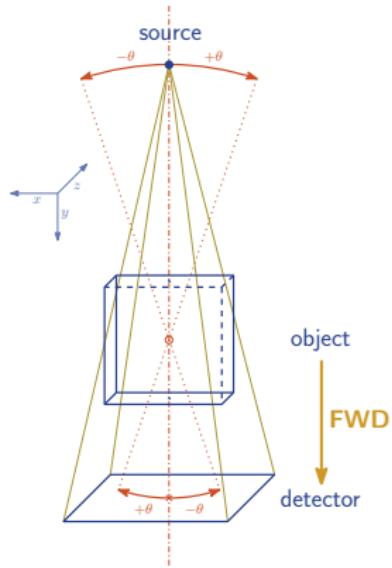
²Ren et al, *Med Phys*, 2014

Introduction: cone-beam projections



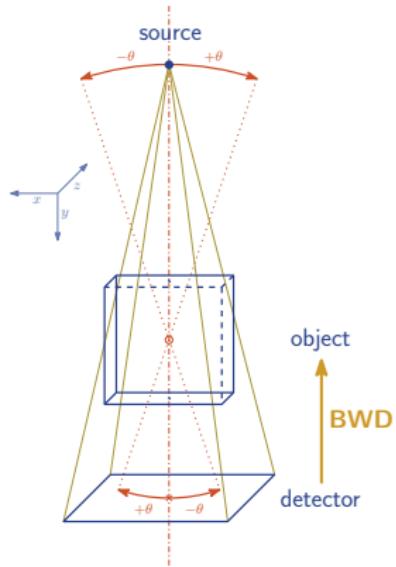
Introduction: cone-beam projections

- forward projections: DRR generation
 - volumetric ray-casting



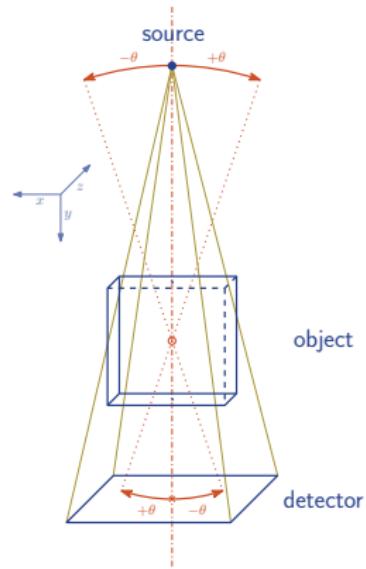
Introduction: cone-beam projections

- forward projections: DRR generation
 - volumetric ray-casting
- backward projections: DVF update
 - filtered back-projection



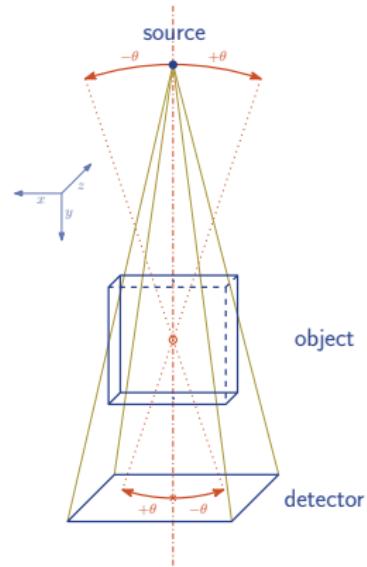
Introduction: cone-beam projections

- forward projections: DRR generation
 - volumetric ray-casting
- backward projections: DVF update
 - filtered back-projection
- LIVE context
 - therapeutic time window (challenge)
 - fixed projection geometry (opportunity)



Introduction: cone-beam projections

- forward projections: DRR generation
 - volumetric ray-casting
- backward projections: DVF update
 - filtered back-projection
- LIVE context
 - therapeutic time window (challenge)
 - fixed projection geometry (opportunity)
 - hours → minutes → seconds

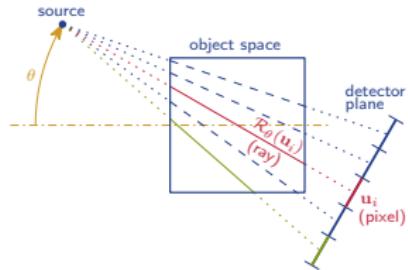


Purpose (3-fold)

- projector abstraction for:
 - faster projection computation
 - higher accuracy
 - adaptation to beam geometry & source trajectory

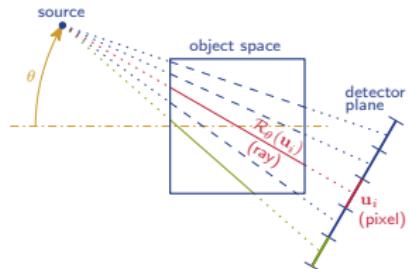
Introduction: digital projector abstraction

physical model

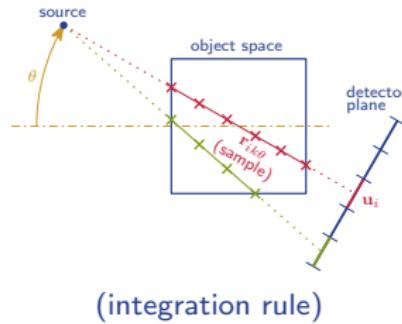


Introduction: digital projector abstraction

physical model

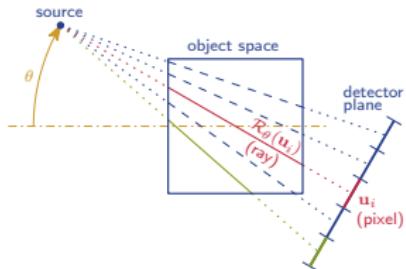


ray-grid sampling for line integral discretization

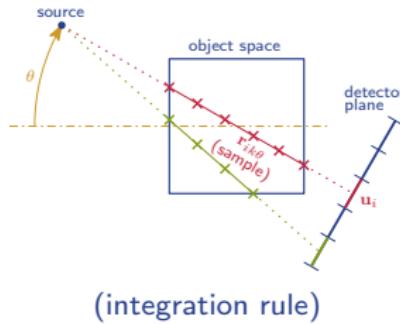


Introduction: digital projector abstraction

physical model

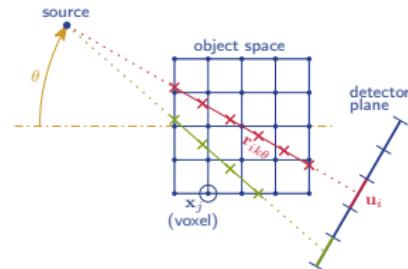


ray-grid sampling for line integral discretization



(integration rule)

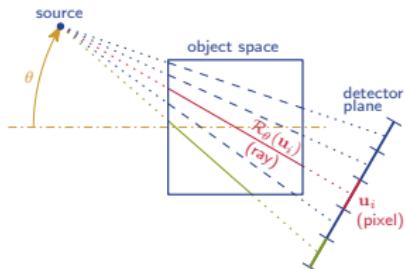
Cartesian re-gridding for registration/rendering



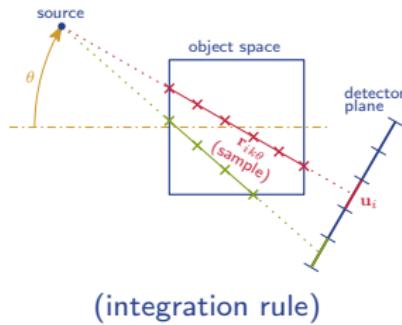
(interpolation kernel)

Introduction: digital projector abstraction

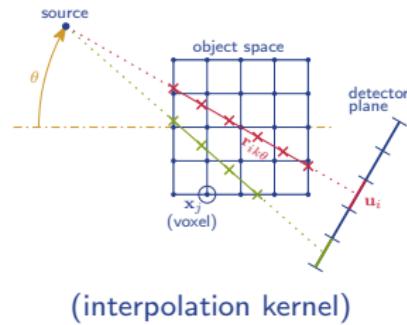
physical model



ray-grid sampling for line integral discretization



Cartesian re-gridding for registration/rendering



$\mathbf{A}(\theta)$: projection matrix

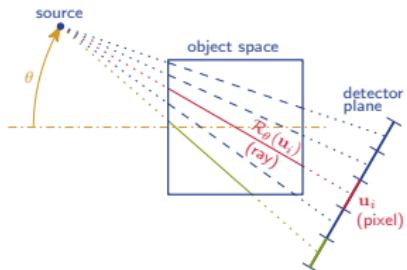
$$\mathbf{p}_\theta = \mathbf{A}(\theta)\mathbf{v}$$

\mathbf{p}_θ : projection image (DRR)

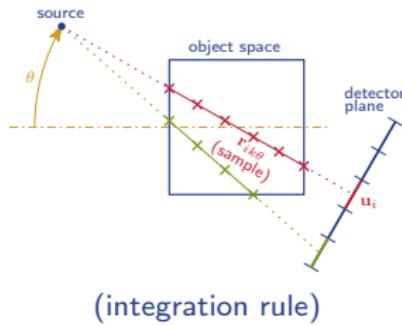
\mathbf{v} : object volume

Introduction: digital projector abstraction

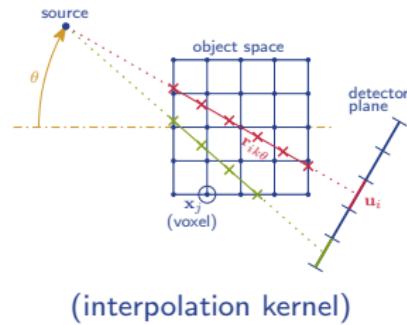
physical model



ray-grid sampling for line integral discretization



Cartesian re-gridding for registration/rendering



$\mathbf{A}(\theta)$: projection matrix

same $\mathbf{A}(\theta)$ across iterations

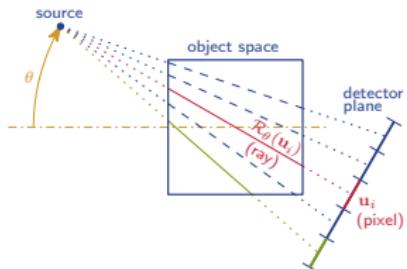
$$\mathbf{p}_\theta = \mathbf{A}(\theta)\mathbf{v}$$

\mathbf{p}_θ : projection image (DRR)

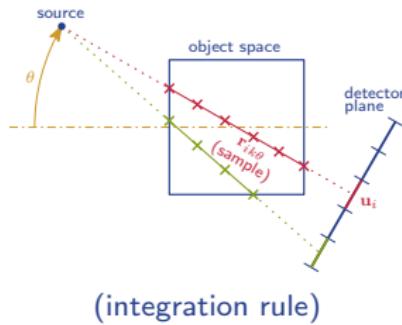
\mathbf{v} : object volume

Introduction: digital projector abstraction

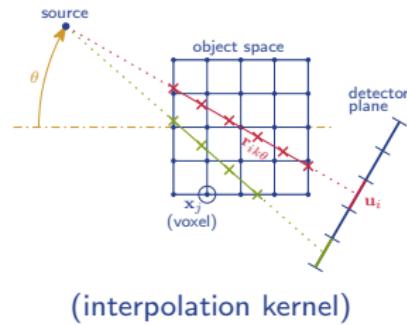
physical model



ray-grid sampling for line integral discretization



Cartesian re-gridding for registration/rendering



$$\mathbf{A}(\theta): \text{projection matrix}$$

same $\mathbf{A}(\theta)$ across iterations

$$\mathbf{p}_\theta = \mathbf{A}(\theta)\mathbf{v}$$

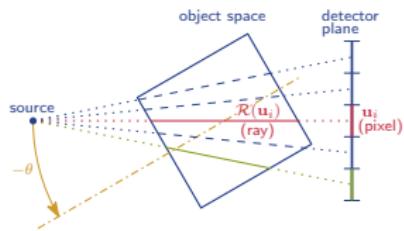
\mathbf{p}_θ : projection image (DRR)

too large to pre-compute
(> 100 GB)

\mathbf{v} : object volume

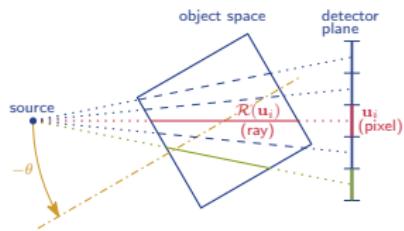
Method: factored projector abstraction

physical model

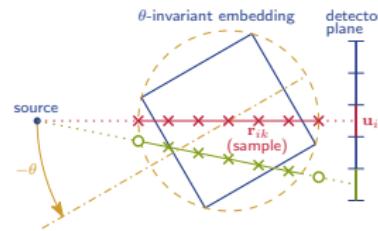


Method: factored projector abstraction

physical model



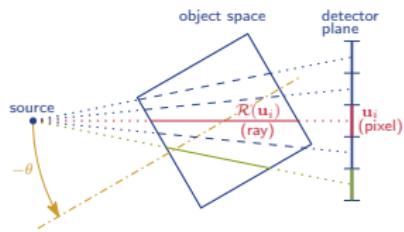
ray-grid sampling for line integral discretization



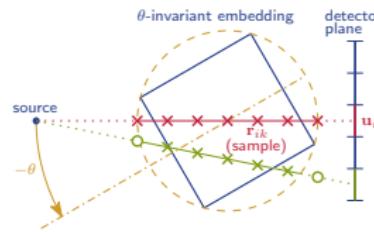
(integration rule)

Method: factored projector abstraction

physical model

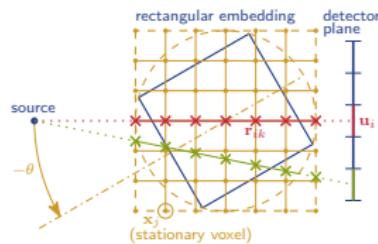


ray-grid sampling for line integral discretization



(integration rule)

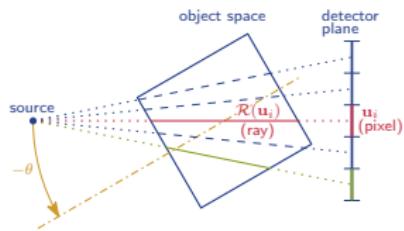
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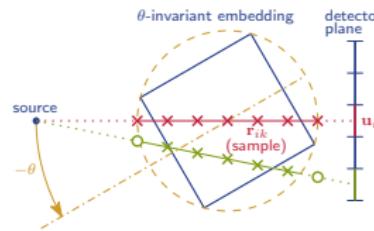
(interpolation sub-kernels)

Method: factored projector abstraction

physical model

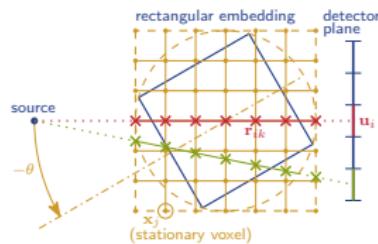


ray-grid sampling for line integral discretization



(integration rule)

Cartesian re-gridding for registration/rendering

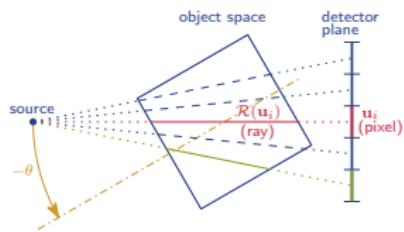


(interpolation sub-kernels)

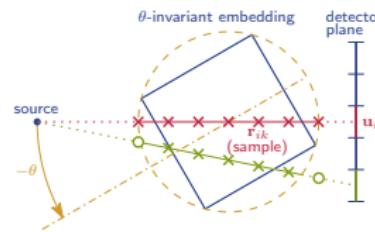
$$\mathbf{p}_\theta = \mathbf{A}(0^\circ)\mathbf{B}(\theta)\mathbf{v}$$

Method: factored projector abstraction

physical model

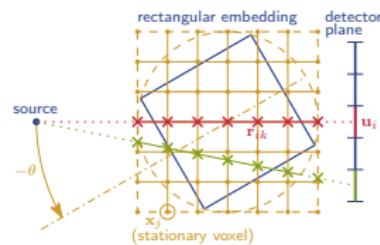


ray-grid sampling for line integral discretization



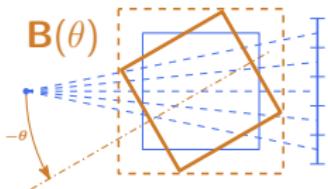
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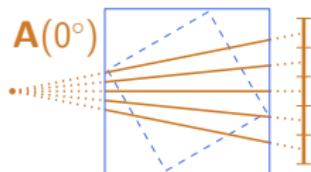
(interpolation sub-kernels)

gantry-relative object rotation



$$\mathbf{p}_\theta = \mathbf{A}(0^\circ)\mathbf{B}(\theta)\mathbf{v}$$

static beam coefficients



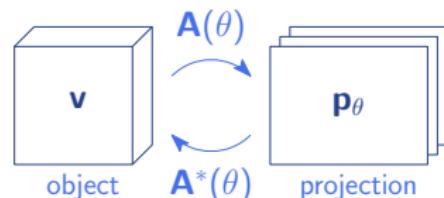
Projector factorization & pre-computation

- previous work: on-the-fly computations
 - geometric abstraction^{1,2}; acceleration^{3–6}; projection model^{7–10}

projection operators
(fixed geometry) operands
(variable data)

$$\mathbf{p}_\theta = \mathbf{A}(\theta) \mathbf{v}$$

too costly
to pre-compute



¹Wiesent *et al*, 2000
⁶Marchelli *et al*, 2013

²Galigekere *et al*, 2003
⁷Mensmann *et al*, 2011

³Nöel *et al*, 2010
⁸Gao, 2012

⁴Dorgham, 2011
⁹Fisher *et al*, 2013

⁵Zinsser & Keck, 2012
¹⁰Choi *et al*, 2014

Projector factorization & pre-computation

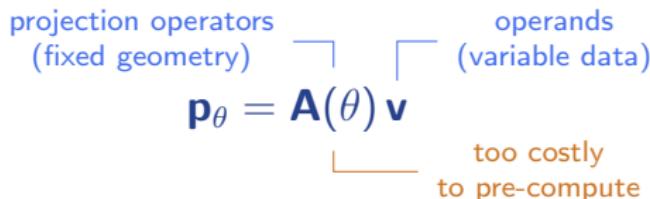
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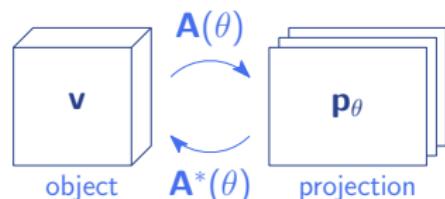
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$$\mathbf{p}_\theta = \mathbf{A}(\theta) \mathbf{v}$$

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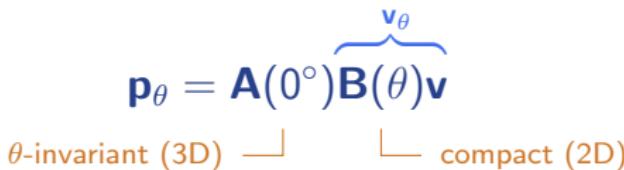


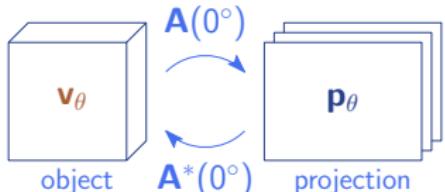


- our contribution: pre-computed projectors (factor abstraction)
 - highly reduced processing, modest memory overhead (<10 GB)

$$\mathbf{p}_\theta = \mathbf{A}(0^\circ) \mathbf{B}(\theta) \mathbf{v}_\theta$$

θ -invariant (3D) compact (2D)





¹Wiesent *et al.*, 2000

²Galigekere *et al.*, 2003

³Nöel *et al.*, 2010

⁴Dorgham, 2011

⁵Zinsser & Keck, 2012

⁶Marchelli *et al.*, 2013

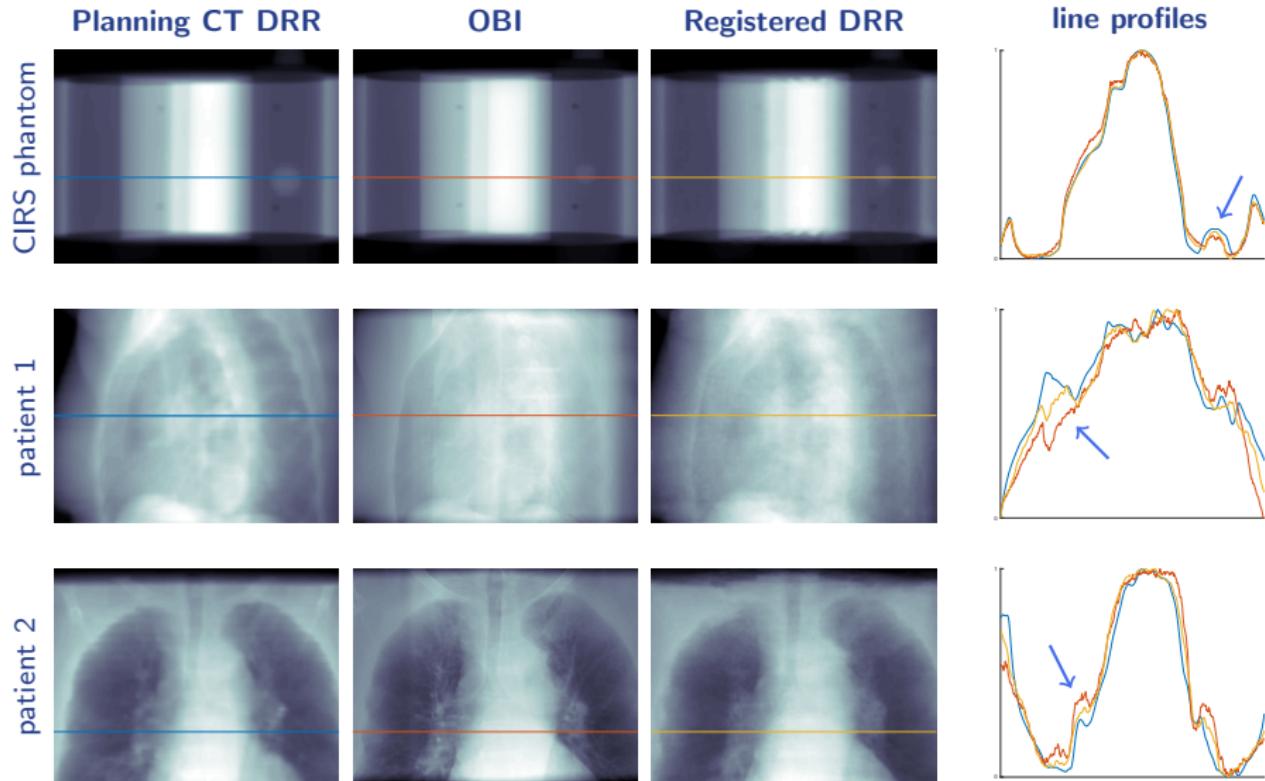
⁷Mensmann *et al.*, 2011

⁸Gao, 2012

⁹Fisher *et al.*, 2013

¹⁰Choi *et al.*, 2014

Results: DRR line profiles



Results: performance

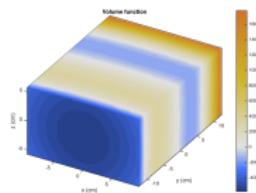
	Planning CT DRR	OBI	Registered DRR	
CIRS phantom				<p># projections: 62 # iterations: 20 1m25s (from 1h30m^{1,2}) 60×</p>
patient 1				<p># projections: 223 # iterations: 33 6m22s</p>
patient 2				<p># projections: 183 # iterations: 30 5m23s</p>

¹Yan et al, *Med Phys*, 2007

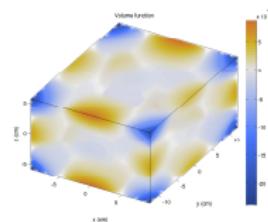
²Zhang et al, *Med Phys*, 2013

Results: digital projector accuracy

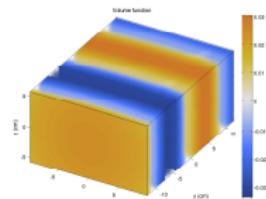
- analytical phantom tests
- higher-order kernels (integration/interpolation)
 - improved accuracy
 - uncompromised speed



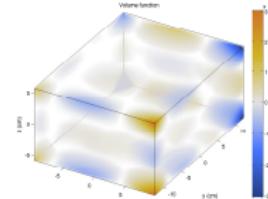
(a) radial polynomial



(c) Cartesian polynomial



(b) radial sinc



(d) Cartesian polynomial

DRR maximum relative error w.r.t. analytical projection

integration/interpolation	(a)	(b)	(c)	(d)
midpoint/linear	$7 \cdot 10^{-5}$	$3 \cdot 10^{-4}$	$9 \cdot 10^{-2}$	1.3
Simpson/cubic	$1 \cdot 10^{-11}$	$1 \cdot 10^{-8}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-5}$

Conclusions

- efficient projection computations
 - elimination of redundancy (geometry & coefficients)
 - low memory overhead
- digital projection accuracy control
 - higher-order kernels without compromising performance
- adaptive to acquisition geometry
 - beam geometry **A** — e.g. ray pencils, fan-beam
 - source trajectory **B**(θ) — e.g. helical
- HW/SW acceleration approaches applicable for further speed-up

Thank you!

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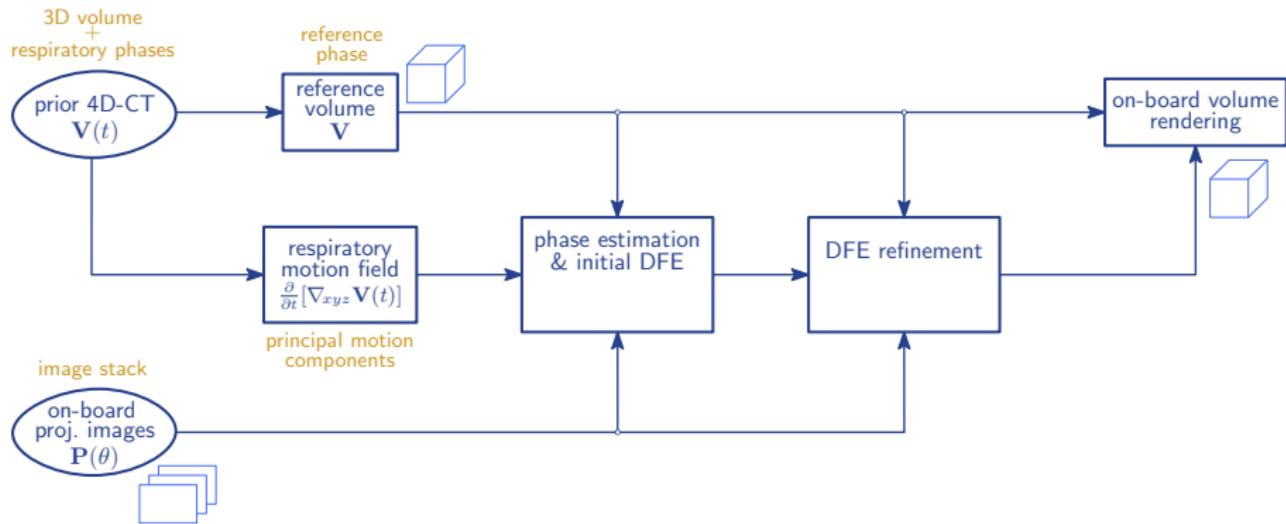
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References V

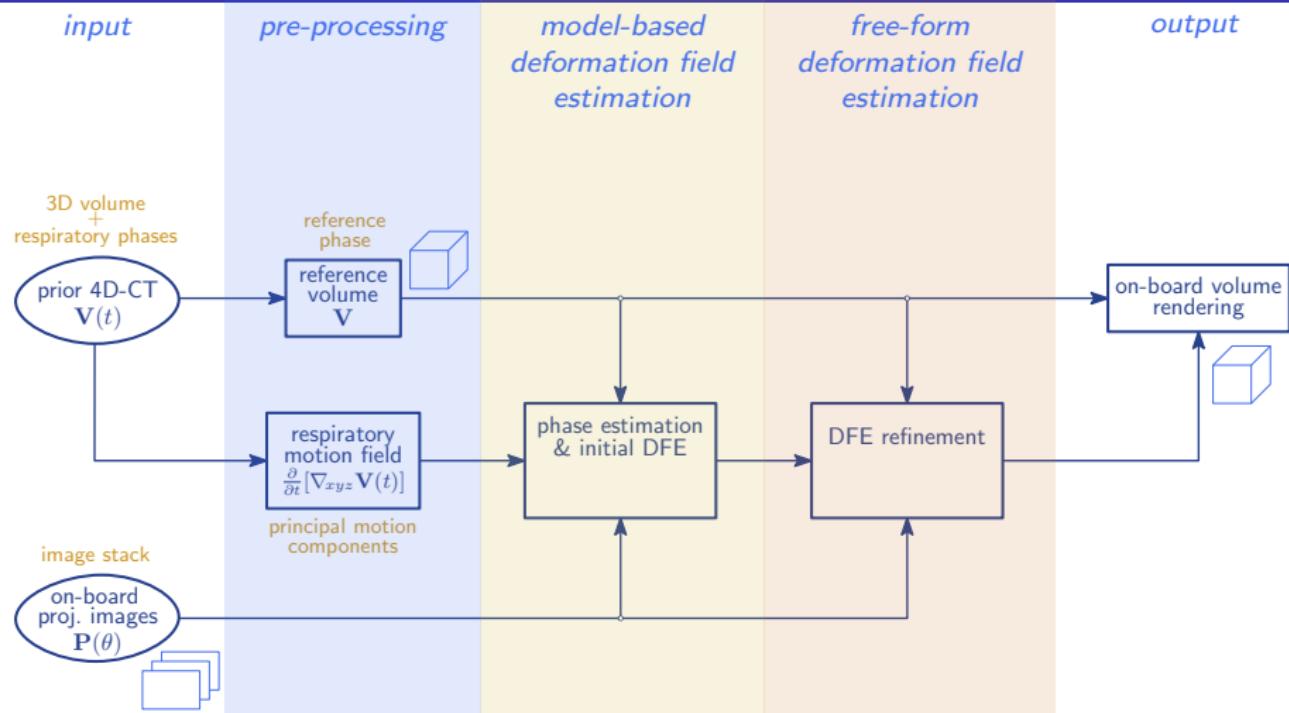
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LIVE algorithm¹



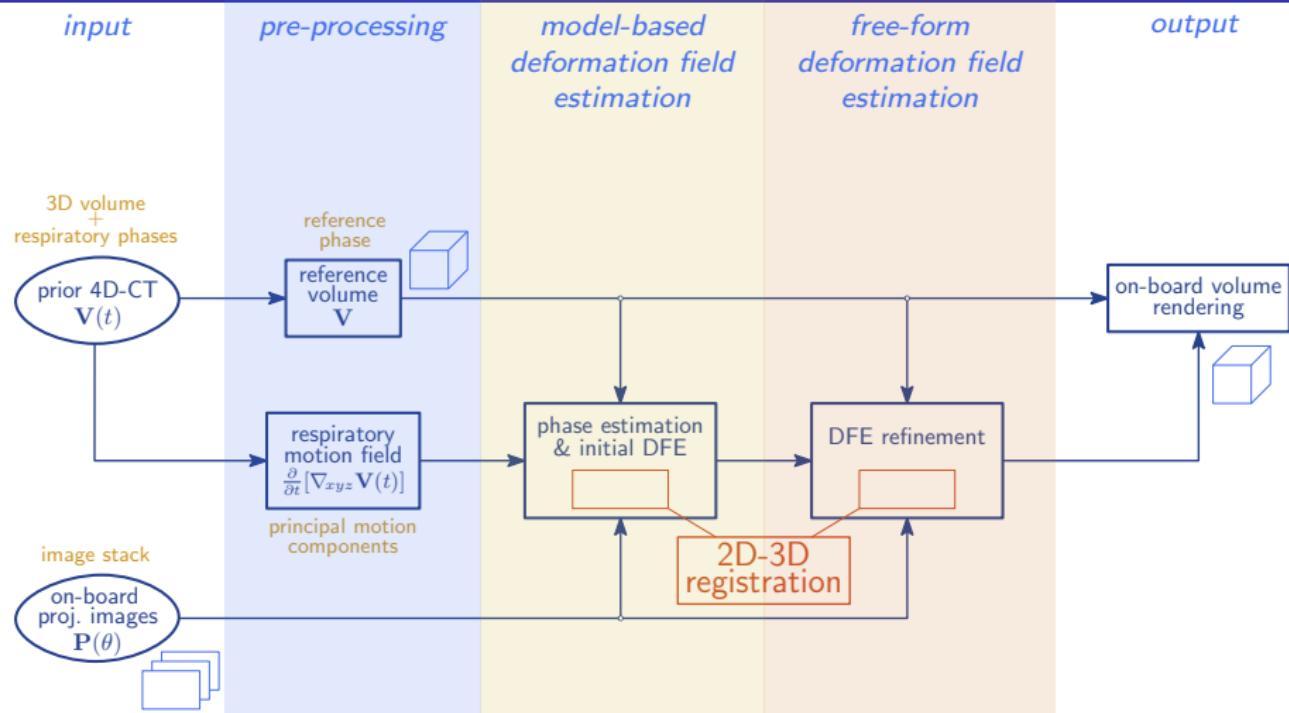
¹Zhang et al,
Med Phys, 2013

LIVE algorithm¹



¹Zhang et al,
Med Phys, 2013

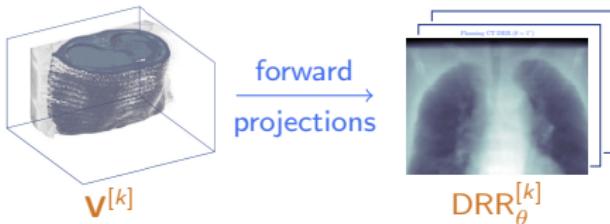
LIVE algorithm¹



¹Zhang et al,
Med Phys, 2013

Iterative DRR-OBI registration (2D/3D)

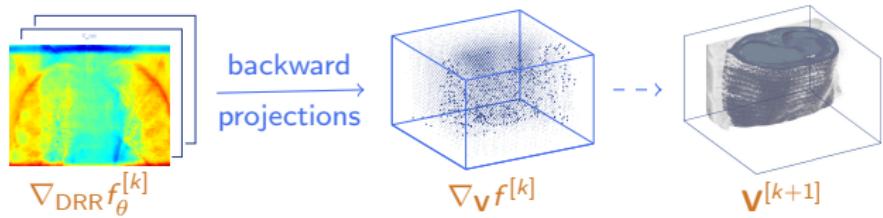
1. Digitally reconstructed radiographs (DRRs)



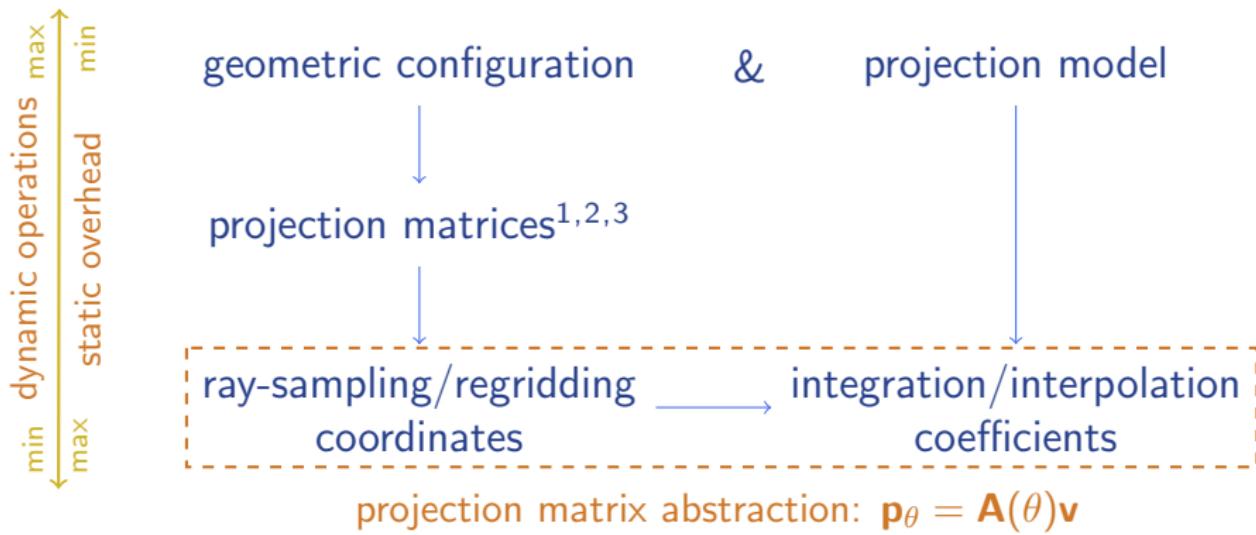
2. Registration fidelity w.r.t. on-board images (OBIs)

$$f\left(\begin{array}{c} \text{DRR}_\theta^{[k]} \\ \text{OBI}_\theta^{[k]} \end{array}\right) = \sum_\theta f_\theta^{[k]}$$

- ### 3. Deformation vector field (DVF) update



Projector abstractions



- staged, modular discretization of operators
- hide modeling details & assumptions from computational model
 - e.g. higher-order numerical integration and regridding kernels

¹Wiesent *et al*, IEEE TMI, 2000

²Galigekere *et al*, IEEE TMI, 2003

³Zinsser & Keck, Fully3D, 2013