Outline

1. Introduction: IGRT & LIVE
2. Cone-beam operators
3. Experiments
4. Discussion
5. Acknowledgements
Outline

1 Introduction: IGRT & LIVE
2 Cone-beam operators
3 Experiments
4 Discussion
5 Acknowledgements
Image-guided radiation therapy (IGRT)

- Highly focused radiation delivery
  - Can eliminate early-stage cancer
  - Accurate targeting is critical

- Volumetric imaging information
  - Pre-treatment planning (above)
  - On-board target verification during treatment
  - Post-evaluation
Image-guided radiation therapy: challenges

- **Dynamic deformation:**
  - Intrafraction (respiration, etc)
  - Tumor displacement, growth/shrinkage
  - Deviates from planning data
  - Hampers targeting precision
  - Complicates projection registration

- **Clinical considerations for on-board imaging:**
  - Low dose
  - Rapid acquisition
  - High-fidelity, fast digital processing

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1. Redmond et al. *IJROBP* (75), 2009
Digital Tomosynthesis (DTS) with LIVE

**CBCT (full scan)**

- Scan angle: $360^\circ / \sim 200^\circ$
- Scan time: $\sim 1$ min
- Scan dose: $1 \sim 8$ cGy

**DTS (limited-angle scan)**

- Scan angle: $20^\circ \sim 60^\circ$
- Scan time: $< 10$ sec
- Scan dose: $\leq 1$ cGy
Digital Tomosynthesis (DTS) with LIVE

**CBCT (full scan)**
- Scan angle: 360° / ~ 200°
- Scan time: ~ 1 min
- Scan dose: 1 ~ 8 cGy

**DTS (limited-angle scan)**
- Scan angle: 20° ~ 60°
- Scan time: < 10 sec
- Scan dose: ≤ 1 cGy

LIVE goal
LIVE overview

- **Purpose:** High-fidelity reconstruction of dynamic volume from limited-angle on-board projections
  - LIVE is the first prototype of its kind

- **Key idea:**
  - Use 4D planning CT as prior data
  - Model on-board volume as deformation of prior CT

- **Methods:**
  - Prior respiratory motion model + free-form (voxel-wise) deformation field
  - Complementary kV-MV projections
  - Iterative deformable registration (computation-intensive)

Ren *et al.* *IJROBP* (82), 2012
Zhang *et al.* *Medical Physics* (40), 2013
Ren *et al.* *Medical Physics* (41), 2014
LIVE imaging/therapy system

One of the radiosurgery systems at Duke (Novalis Tx)\(^1\)

\(^1\)Chang et al. *JACMP* (33), 2012
LIVE imaging/therapy system

One of the radiosurgery systems at Duke (Novalis Tx)$^1$

$kV$ source

$MV$ detector

radiotherapy/$MV$

$kV$ detector

$^1$Chang et al. JACMP (33), 2012
LIVE DTS algorithm

1. Prior 4D-CT $V(\phi)$
2. Reference volume $V(\phi_r)$
3. Respiratory motion field $\frac{\partial}{\partial \phi} [\nabla_{xyz} V(\phi)]$ (principal motion components)
4. Phase selection
5. Phase estimation & initial DFE refinement
6. DFE refinement
7. On-board volume rendering

LIVE DTS algorithm

**input**

3D volume + respiratory phases

prior 4D-CT \( V(\phi) \)

**pre-processing**

phase selection

reference volume \( V(\phi_r) \)

respiratory motion field \( \frac{\partial}{\partial \phi} [\nabla_{xyz} V(\phi)] \)

principal motion components

**model-based deformation field estimation**

phase estimation & initial DFE

DRR-OBI registration

**free-form deformation field estimation**

DFE refinement

**output**

on-board volume rendering

**on-board proj. images** \( P(\theta) \)

**image stack**

LIVE DTS algorithm

1. Prior 4D-CT $V(\phi)$
2. Phase selection
3. Respiratory motion field $\frac{\partial}{\partial \phi} [\nabla_{xyz} V(\phi)]$
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LIVE DTS algorithm

1. Prior 4D-CT volume $V(\phi)$
2. Phase selection of reference volume $V(\phi_r)$
3. Respiratory motion field $\frac{\partial}{\partial \phi}[\nabla_{xyz} V(\phi)]$
4. Phase estimation and initial DFE
5. DFE refinement
6. On-board volume rendering

- 3D volume + respiratory phases
- On-board proj. images $P(\theta)$
- Image stack
- Principal motion components
- (Iterative) computational bottleneck

Zhang et al. Med Phys (40), 2013
Iterative DRR-OBI registration

1. Digitally reconstructed radiographs (DRRs) for volume-image registration

2. Registration fidelity

3. Deformation field estimate (DFE) update along pixel and voxel gradients
A glance at output and timing

Planning CT DRR

OBI

DTS DRR

1m25s vs. 1h30m

6m22s

5m23s

1 \textsuperscript{1} Yan et al. Medical Physics (34), 2007

2 \textsuperscript{2} Zhang et al. Medical Physics (40), 2013
Forward & backward cone-beam projections

Forward projections: DRR generation
- Volumetric ray-casting operator (primary effects)
- Secondary effects (scatter, etc) beyond this talk

Backward projections: DFE update
- Filtered back-projection operator

Clinical/DTS context
- Fixed projection geometry
- Processing within clinical response time (order of seconds)

Staub & Murphy. *Medical Physics* (40), 2013
Feldkamp *et al.* *JOSAA* (1), 1984
Katsevich. *IJMMS* (21), 2003
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- **Forward projections**: DRR generation
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GTC15 March 19, 2015 12 / 29
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A simple fact & a long battle

\[ p_{\theta}^{[k]} = A(\theta) v^{[k]} \]
A simple fact & a long battle

\[ p^{[k]}_\theta = A(\theta) v^{[k]} \]

- \( \{A(\theta) \mid \theta \in \Theta\} \): pre-computable in theory

- Challenging in practice (past\(^1\),\(^2\) to present)
  - Memory capacity & communication bandwidth

---

\(^1\)Levoy. PhD thesis, UNC, 1989
\(^2\)Xu & Mueller. IEEE TNS, 2005
A simple fact & a long battle

projection operators (fixed geometry)  
\[ p^{[k]}_\theta = A(\theta) v^{[k]} \]

operands (variable across iterations)

- \(\{A(\theta) \mid \theta \in \Theta\}\): pre-computable in theory

- Challenging in practice (past\textsuperscript{1,2} to present)
  - Memory capacity & communication bandwidth

<table>
<thead>
<tr>
<th>(N_v)</th>
<th>(N_p)</th>
<th>(N_\Theta)</th>
<th>(\tilde{N}_R)</th>
<th>(S_N)</th>
<th>Memory (GiB)</th>
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<tr>
<td>256×256×160</td>
<td>512×384</td>
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<td>256</td>
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<td>60</td>
<td>512</td>
<td>2×2×2</td>
<td>903.8</td>
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</tbody>
</table>

\textsuperscript{1}Levoy. \textit{PhD thesis}, UNC, 1989
\textsuperscript{2}Xu & Mueller. \textit{IEEE TNS}, 2005
Precursors and contribution

\[ p_{\theta}^{[k]} = A(\theta) v^{[k]} \]

\( \theta \)-dependent & large

- On-the-fly computations
  - HW/SW acceleration\(^1,2,3,4,5\)
  - Fourier-based methods\(^6,7\)
  - Ray/volume models\(^8,9,10\)
  - Fast ray descriptors\(^11,12\)
  - ...

- Lightweight pre-computations
  - Modest memory cost
- Fast on-line processing
  - Substantially reduced complexity
  - GPU-friendly

\[ p_{\theta}^{[k]} = A(0^\circ) B(\theta)v^{[k]} \]

---

1 Nôel et al, 2010
2 Park et al, 2011
3 Dorgham et al, 2011
4 Jia et al, 2012
5 Marchelli et al, 2013
6 Lacroute & Levoy, 1994
7 Choi et al, 2014
8 Mensmann et al, 2011
9 Gibou & Bertelli, 2012
10 Fisher et al, 2013
11 Siddon, 1985
12 Gao, 2012
Precursors and contribution

\[ \mathbf{p}_\theta^{[k]} = \mathbf{A}(\theta) \mathbf{v}^{[k]} \]

θ-dependent & large

• On-the-fly computations
  – HW/SW acceleration\(^1,2,3,4,5\)
  – Fourier-based methods\(^6,7\)
  – Ray/volume models\(^8,9,10\)
  – Fast ray descriptors\(^11,12\)
  – ...

• Lightweight pre-computations
  – Modest memory cost
  – Substantially reduced complexity
  – GPU-friendly

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

\(\mathbf{v}_\theta^{[k]}\)

\(\mathbf{A}(0^\circ)\)

\(\mathbf{A}^*(0^\circ)\)

\([k]\)

\([k]\)

\([k]\)
Digital projection methods: **coupled** (object-centric)

**physical model**

\[ p^c_{\theta}(u_i) = \int_{R^c_\theta(u_i)} v(u_i, \rho) \, d\rho \]
Digital projection methods: **coupled** (object-centric)

**physical model**

**ray-grid sampling**

\[ p^c_\theta(u_i) = \int_{\mathcal{R}_\theta(u_i)} v(u_i, \rho) \, d\rho \]

\[ p_\theta(u_i) = \sum_{\rho_k \in \mathcal{R}_\theta(u_i)} w_{ik\theta} v(r_{ik\theta}) \]
Digital projection methods: **coupled** (object-centric)

**physical model**

\[
p^c_\theta(u_i) = \int_{R^c_\theta(u_i)} v(u_i, \rho) \, d\rho
\]

**ray-grid sampling**

\[
p_\theta(u_i) = \sum_{\rho_k \in R_\theta(u_i)} w_{ik\theta} \, v(r_{ik\theta})
\]

**Cartesian re-gridding**

\[
v(r_{ik\theta}) \approx \sum_{x_j \in N(r_{ik\theta})} h_{ijk\theta} \, v(x_j)
\]

\[
I_{\theta}(u_i) = \int_{R^c_\theta(u_i)} v(u_i, \rho) \, d\rho
\]

\[
p_\theta(u_i) = \sum_{\rho_k \in R_\theta(u_i)} w_{ik\theta} \, v(r_{ik\theta})
\]

\[
v(r_{ik\theta}) \approx \sum_{x_j \in N(r_{ik\theta})} h_{ijk\theta} \, v(x_j)
\]
Digital projection methods: **factored** (gantry-centric)

\[
p^c_{\theta}(u_i) = \int_{\mathcal{R}^c(u_i)} \nu_\theta(u_i, \rho) \, d\rho
\]
**Digital projection methods: factored (gantry-centric)**

**Physical model**

- Source
- Object space
- Detector plane
- \( \theta \)
- \( y \)
- \( x \)
- \( u_i \)
- \( R(u_i) \) (ray)
- \( p_c(\theta) = \int_{\mathcal{R}(u_i)} v_{\theta}(u_i, \rho) \, d\rho \)

**Ray-grid sampling**

- Source
- Object space
- Detector plane
- \( \theta \)-invariant embedding
- \( r_{ik} \)
- \( u_i \)
- \( p(\theta) = \sum_{\rho_k \in \mathcal{R}(u_i)} w_{ik} v_{\theta}(r_{ik}) \)

\[ p_c(\theta) = \int_{\mathcal{R}(u_i)} v_{\theta}(u_i, \rho) \, d\rho \]

\[ p(\theta) = \sum_{\rho_k \in \mathcal{R}(u_i)} w_{ik} v_{\theta}(r_{ik}) \]
Digital projection methods: **factored** (gantry-centric)

**Physical model**

- Object space
- Detector plane
- Source

**Ray-grid sampling**

- \[ p^c_\theta(u_i) = \int_{\mathcal{R}_c(u_i)} v_\theta(u_i, \rho) \, d\rho \]
- \[ p_\theta(u_i) = \sum_{\rho_k \in \mathcal{R}(u_i)} w_{ik} v_\theta(r_{ik}) \]

**Cartesian re-gridding**

- Rectangular embedding
- Detector plane

\[ v_\theta(r_{ik}) \simeq \sum_{x_j \in \mathcal{N}(r_{ik})} h_{ijk} \bar{v}_\theta(x_j) \]

\[ \bar{v}_\theta(x_j) \simeq \sum_{x'_j \in \mathcal{N}_\theta(x_j)} h_{jj'}^{\text{traj}} v(x'_j) \]
Digital projection methods: comparison

**coupled**

\[
p_{\theta}(u_i) \simeq \sum_{r_{ik\theta} \in \mathcal{R}_{\theta}(u_i)} w_{ik\theta} \sum_{x_j \in \mathcal{N}(r_{ik\theta})} h_{ijk\theta} v(x_j)
\]

**factored**

\[
\overline{v}_{\theta}(x_j) \simeq \sum_{x_j' \in \mathcal{N}_{\theta}(x_j)} h_{\text{traj}}^{ij'} v(x_j')
\]

\[
p_{\theta}(u_i) \simeq \sum_{r_{ik} \in \mathcal{R}(u_i)} w_{ik} \sum_{x_j \in \mathcal{N}(r_{ik})} h_{\text{ray}}^{ij} \overline{v}_{\theta}(x_j)
\]
Digital projection methods: comparison

**coupled**

\[ p_\theta(u_i) \simeq \sum_{r_{ik} \in \mathcal{R}_\theta(u_i)} w_{ik\theta} \sum_{x_j \in \mathcal{N}(r_{ik}\theta)} h_{ijk\theta} v(x_j) \]

**factored**

\[ v_\theta(x_j) \simeq \sum_{x_j' \in \mathcal{N}_\theta(x_j)} h_{jj'\theta}^{\text{traj}} v(x_j') \]

\[ p_\theta(u_i) \simeq \sum_{r_{ik} \in \mathcal{R}(u_i)} w_{ik} \sum_{x_j \in \mathcal{N}(r_{ik})} h_{ijk}^{\text{ray}} v(x_j) \]

\[ \bar{v}_\theta \simeq \left[ (C_{\text{traj}}(\theta) M_{\text{traj}}(\theta)) \otimes I_z \right] v \]

\[ p_\theta \simeq C_{\text{ray}} M_{\text{ray}} \bar{v}_\theta \]

- **C**: composite coefficients
- **M**: geometric index mapping

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Fast Digital Tomosynthesis for LIVE Radiation Therapy

GTC15 March 19, 2015 17 / 29
Digital projection methods: comparison

**coupled**

- $\theta$-dependent ray projectors

**factored**

- slice-invariant rotation
- $\theta$-invariant ray projector

$\mathbf{p}_\theta \approx \mathbf{C}(\theta) \mathbf{M}(\theta) \mathbf{v}$

- $\mathbf{C}$: composite coefficients
- $\mathbf{M}$: geometric index mapping

$\overline{\mathbf{v}}_\theta \approx [\mathbf{C}_{\text{traj}}(\theta) \mathbf{M}_{\text{traj}}(\theta) \otimes \mathbf{I}_z] \mathbf{v}$

$\mathbf{p}_\theta \approx \mathbf{C}_{\text{ray}} \mathbf{M}_{\text{ray}} \overline{\mathbf{v}}_\theta$
Digital projection methods: comparison

**Coupled**
- $\theta$-dependent ray projectors
- one-step computations
- no embedding

$p_\theta \approx C(\theta) \, M(\theta) \, v$

**Factored**
- slice-invariant rotation
- $\theta$-invariant ray projector
- up to $2 \times$ embedding domain size

$\overline{v}_\theta \approx [(C_{\text{traj}}(\theta) \, M_{\text{traj}}(\theta)) \otimes I_z] \, v$

$p_\theta \approx C_{\text{ray}} \, M_{\text{ray}} \, \overline{v}_\theta$

* C: composite coefficients
  M: geometric index mapping
Re-composable operators

\[ b \cong C M a \]

- **Static-dynamic decoupling**
  - Pre-computed operators (\(C\) and \(M\))
  - Simple computations with dynamic operands
- **Flexible operator composition for improved accuracy**
  - Ray projection (quadrature)\(^1\)
  - Regridding (interpolation kernel)\(^2\)
- **Additional potential for performance tuning**
  - Known memory access patterns
  - Mapping to memory architecture (global/texture)

\(^1\)Engels. *Academic Press*, 1980
\(^2\)Lehmann et al. *IEEE TMI* (18), 1999
Space and time complexities

Space (pre-computed coefficients)

- \( M_{oc} = N_p \tilde{N}_R N_\Theta S_N \)
- \( M_{gc} = N_p \tilde{N}_R S_{N}^{ray} + N_v^{xy} N_\Theta S_{N}^{traj} \)

Time (online computations)

- \( T_{oc} \)
- \( T_{gc} \)

\( N_p \): # of DRR pixels
\( \tilde{N}_R \): average # of samples per ray
\( N_\Theta \): # of projection angles
\( N_v \): # of CT voxels
\( S_N \): neighborhood size of regridding kernel

same for helical and saddle source trajectories
Space and time complexities

Space (pre-computed coefficients)

- \( M_{oc} = N_p \tilde{N}_R N_\Theta S_N = K_{oc} \)
- \( M_{gc} = N_p \tilde{N}_R S_N^{\text{ray}} + N_v^{xy} N_\Theta S_N^{\text{traj}} = K_{gc}^{\text{ray}} + K_{gc}^{\text{traj}} \)

Time (online computations)

- \( T_{oc} = K_{oc} \)
- \( T_{gc} = K_{gc}^{\text{ray}} N_\Theta + K_{gc}^{\text{traj}} N_v^z \)

\( N_p \) : # of DRR pixels
\( \tilde{N}_R \) : average # of samples per ray
\( N_\Theta \) : # of projection angles
\( N_v \) : # of CT voxels
\( S_N \) : neighborhood size of regridding kernel

same for helical and saddle source trajectories
Space and time complexities

Space (pre-computed coefficients)

- \[ M_{oc} = N_p \tilde{N}_R N_\Theta S_N = K_{oc} \]
- \[ M_{gc} = N_p \tilde{N}_R S_N^{ray} + N_v^{xy} N_\Theta S_N^{traj} = K_{ray}^{gc} + K_{traj}^{gc} \]

Time (online computations)

- \[ T_{oc} = K_{oc} \]
- \[ T_{gc} = K_{ray}^{gc} N_\Theta + K_{traj}^{gc} N_v^z \]

<table>
<thead>
<tr>
<th>Set</th>
<th>Model settings</th>
<th>Space (GiB)</th>
<th>Time* (GFLOP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_v ) ( N_p ) ( N_\Theta ) ( \tilde{N}_R ) ( S_N )</td>
<td>O-C</td>
<td>G-C</td>
</tr>
<tr>
<td>A</td>
<td>256\times256\times160</td>
<td>512\times384</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>256\times256\times160</td>
<td>512\times384</td>
<td>60</td>
</tr>
<tr>
<td>C</td>
<td>256\times256\times160</td>
<td>512\times384</td>
<td>60</td>
</tr>
<tr>
<td>D</td>
<td>512\times512\times320</td>
<td>1024\times768</td>
<td>60</td>
</tr>
</tbody>
</table>

O-C: object-centric (coupled); G-C: gantry-centric (factored)
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CT/OBI data-sets

(phantom) $256 \times 256 \times 136$

(patient 1) $256 \times 256 \times 136$

(patient 2) $256 \times 256 \times 166$

(512 $\times 384) \times 62$

(512 $\times 384) \times 223$

(512 $\times 384) \times 182$
Results: phantom

Planning CT DRR  OBI  DTS DRR  

$\theta = 1^\circ$

$\theta = 15^\circ$

$\theta = 90^\circ$
Results: phantom

- \( \theta = 1^\circ \)
- \( \theta = 15^\circ \)
- \( \theta = 90^\circ \)

- # projections: 62
- # iterations: 2 + 18
- Elapsed time: 1m25s
- Old time: \( \sim 60 \times \) 1h30m

\(^1\)Yan et al. Medical Physics (34), 2007
\(^2\)Zhang et al. Medical Physics (40), 2013
Results: patient 1

<table>
<thead>
<tr>
<th>Planning CT DRR</th>
<th>OBI</th>
<th>DTS DRR</th>
<th>line profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image of Planning CT DRR" /></td>
<td><img src="image2" alt="Image of OBI" /></td>
<td><img src="image3" alt="Image of DTS DRR" /></td>
<td><img src="image4" alt="Image of line profiles" /></td>
</tr>
</tbody>
</table>

\[ \theta = 1^\circ \]

\[ \theta = 30^\circ \]

\[ \theta = 60^\circ \]
Results: patient 1

- # projections: 223
- # iterations: 10 + 23
- Elapsed time: 6m22s
Results: patient 2

Planning CT DRR | OBI | DTS DRR | line profiles

$\theta = 1^\circ$

$\theta = 30^\circ$

$\theta = 60^\circ$
Results: patient 2

θ = 1°

θ = 30°

θ = 60°

- # projections: 182
- # iterations: 10 + 20
- Elapsed time: 5m23s
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Recap & remaining challenges

- Re-composable operators: efficiency & flexibility without compromising accuracy
  - abstraction layer: research \(\leftrightarrow\) performance
  - implementation acceleration still applicable

- Further directions:
  - numerical projector composition effect on iterations\(^1\)
  - planning-stage respiratory structure extraction/encoding\(^2\)
  - memory access pattern optimization
  - algorithmic modifications (anatomical structure, low-contrast enhancement)

- LIVE is entering the clinical trials stage

\(^1\)ELEVIT 2015 (submission) \(^2\)AAPM Annual Meeting 2015 (submission)
Acknowledgements

- You Zhang
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  Adjunct Associate Professor, UNC

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References III


