Self-Calibration of Cone-Beam CT Using 3D-2D Image Registration

Sarah Ouadah\textsuperscript{1}
J. Webster Stayman\textsuperscript{1}
Grace Jianan Gang\textsuperscript{1}
Ali Uneri\textsuperscript{2}
Tina Ehtiati\textsuperscript{3}
Jeffrey H. Siewerdsen\textsuperscript{1,2}

1. Department of Biomedical Engineering
2. Department of Computer Science
3. Siemens Healthcare


department of biomedical engineering

Acknowledgements

The I-STAR Lab
Imaging for Surgery, Therapy, and Radiology
http://istar.jhu.edu

Collaborators
Dr. Adam Wang, Johns Hopkins University
Dr. Yoshito Otake, Johns Hopkins University
Dr. Kevin Royalty, Siemens, AX

Funding Support
National Institutes of Health R01-EB-017226
Siemens Healthcare, AX Division
Geometric Calibration

**Describes system geometry**
- 1 set of parameters per projection
- 6 - 9 degrees of freedom (DOF)

**Performed with specialized phantoms**
- BB spiral\(^1\), ellipses\(^2\)
- Performed periodically

**Essential for accurate image reconstruction**
- Errors result in image artifacts

---

1. Navab, U.S. Patent No. 5,923,727, 1999
2. Cho et al, Med Phys, 2005

---

Uncertainty in Geometric Calibration

**Out-of-date geometric calibration**
- Geometric error due to changes over time

**Irreproducible source-detector orbit\(^1\)**
- Vibration, jitter
- C-arm flex under gravity

**Un-calibrated systems**
- Unknown geometry

**Task-driven imaging\(^2\) → Non-circular orbits**
- Robotic C-arm systems capable of general orbits
- Trajectory can be driven by a particular imaging task
- Difficult to obtain an accurate calibration
- Difficult to anticipate all possible trajectories

---

1. Daly et al, Med Phys, 2008
2. Stayman & Siewerdsen, Fully 3D, 2013
Solution Concept: 3D-2D Registration

Method:
Previously acquired 3D image ($\mu_{\text{moving}}$)
Register to 2D projection data ($p_{\text{fixed}}$)
Determine the system pose (T,R) for each projection view ($N_{\text{proj}}$)
Solve transformation parameters representing the system geometry.

Self-Calibration

3D-2D Registration

3D CT Volume
2D Projections

Similarity Metric
NGI

Transformation 6 / 9 DOF
CMA-ES Optimization 6 / 9 DOF
Binning
Population Size
Max evaluations
Tolerance

Final Poses 3x4 Projection Matrices
3D-2D Registration

3D CT Volume

2D Projection

3D-2D Registration

3D CT Volume

2D Projection

Siddon Forward Projector
3D-2D Registration

- 3D CT Volume
- DRR
- 2D Projection
- Similarity Metric

**3D-2D Registration**

\[ NGI(I_F, I_M) = \frac{G(I_M, I_F)}{G(I_F, I_F)} \]

\[ G(I, I) = \sum_{i,j} m(i,j)w(i,j)\min(|\nabla p_1(i,j)|, |\nabla p_2(i,j)|) \]

- Optional Mask
- Weighting based on inner product of gradient vectors
- Robustness against strong gradient mismatch

Otake et al, Phys Med Bio, 2013

---

3D-2D Registration

- 3D CT Volume
- DRR
- 2D Projection
- Similarity Metric

**CMA-ES Optimization**

- Binning = 3
- Population Size = 100
- \( \Delta(T, R) = 0.1 \text{ mm/deg} \)
- Max evaluations = \( 10^6 \)

Hansen & Ostermeier, Evol Comput, 2006
**Experimental Methods**

1. Feasibility Cylinder Phantom, 6 DOF vs 9 DOF
2. Robustness Anthropomorphic Head Phantom
3. Translation Robotic C-Arm System (Zeego)
4. Application Task-Driven Imaging (Non-Circular Orbit)
Experimental Methods

1. Feasibility
Cylinder Phantom, 6 DOF vs 9 DOF

2. Reproducibility
Anthropomorphic Head Phantom

3. Translation
Robotic C-Arm System (Zeego)

4. Application
Non-Circular Orbit (Task-Driven Imaging)

Circular Orbit
360 projections, 360°
70 kVp, 227 mAs

X-Ray Source
Flat Panel Detector
Cone-Beam CT Imaging Bench

1. Cylinder Phantom
Re-Projection Error

Calibration Method
Reference:
6 DOF Self-Cal:
9 DOF Self-Cal:

RPE
0.83 ± 0.01 mm
0.70 ± 0.002 mm
0.71 ± 0.005 mm

Re-Projection Error
3D Point Cloud ➔ Variance ➔ FWHM (RPE)
1. Cylinder Phantom

Reference Calibration
- Wire PSF
  - FWHM = 0.80 ± 0.001 mm

6 DOF Self-Calibration
- FWHM = 0.79 ± 0.01 mm

9 DOF Self-Calibration
- FWHM = 0.80 ± 0.01 mm

Experimental Methods

2. Robustness
Anthropomorphic Head Phantom

Circular Orbit
- 360 projections, 360°
- 70 kVp, 227 mAs

Cone-Beam CT Imaging Bench
2. Anthropomorphic Phantom

Re-Projection Error

RPE
Reference Calibration 0.84 ± 0.06 mm
Self-Calibration 0.60 ± 0.06 mm

FWHM = 0.81 ± 0.01 mm

2. Anthropomorphic Phantom

Reference Calibration

Self-Calibration

FWHM = 0.81 ± 0.02 mm
Experimental Methods

Circular Orbit
496 Projections over 200°
87.2 kVp, 229 mAs

X-Ray Source
Flat Panel Detector

Artis Zeego, Siemens Healthcare

3. Translation
Robotic C-Arm System (Zeego)

3. Robotic C-Arm

Re-Projection Error

<table>
<thead>
<tr>
<th>Calibration</th>
<th>RPE</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>0.80 ± 0.12 mm</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Self-Calibration</td>
<td>0.70 ± 0.12 mm</td>
<td></td>
</tr>
</tbody>
</table>

FWHM = 0.70 ± 0.04 mm

FWHM = 0.65 ± 0.03 mm
3. Robotic C-Arm

Reference Calibration

Self-Calibration

Experimental Methods

4. Application
Task-Driven Imaging
(Non-Circular Orbit)

Non-Circular Orbit
360 projections, 360°
70 kVp, 227 mAs

Flat Panel Detector

Cone-Beam CT Imaging Bench
4. Non-Circular Orbit

Saddle Orbit:
ΔZ: ± 25 mm
ΔY: ± 50 mm

4. Non-Circular Orbit

Reference Calibration
FWHM = 0.83 ± 0.01 mm

Self-Calibration
FWHM = 0.81 ± 0.01 mm
Conclusions

Self-Calibration using 3D-2D registration
Geometric calibration equivalent to (or better than) conventional pre-calibration methods

Potential advantages and utility
- Robustness to out-of-date calibration
- Detection of calibration errors (QA)
- Systems with non-reproducible orbit and/or vibration
- Improve upon (supposedly) well calibrated systems

Enables advanced 3D imaging methods
- Task-driven imaging → Non-circular orbits
- Model-based 3D image reconstruction

Future Work
- Robustness to deformable motion
- Basis for patient motion correction in CBCT
- Evaluation in clinical image data