Seminar Presentation:
Self-calibration of cone-beam CT geometry using 3D-2D image registration

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Group 5 : Ju Young Ahn
Mentor: Dr. Jeff Siewerdsen
Dr. Matthew Jacobson, Dr. Tharindu da Silva, Dr. Joseph Goerres
Project Overview

**Goal:** Develop user-friendly interfaces to simulate fluoroscopic views of mobile C-arm

**Challenge:** “Fluoro-hunting”
- Multiple fluoroscopic shots taken for an optimal view
- Time consuming, radiation exposure, physically cumbersome, safety issue

**Solution:** Digitally Reconstructed Radiograph (DRR) generated from preoperative 3D CT data.
- Less time consuming
- Less radiation exposure for both physicians and patients
- Less user variability, more consistency
Goal: Geometric calibration method that registers the 2D projection data to a previously acquired 3D image of the subject, providing a ‘self calibration’ of the system

Challenges: 1) Out-of-date calibration (over-time, irreproducibility in the orbit)  
2) Complicated non-circular orbits, inability to anticipate all possible trajectories

Relevance: One of our maximum deliverables is 3D-2D patient-CT image registration to get rid of optical tracking system
Technical Approach - Overview

Step 1. Registration is initialized

Step 2. 3D-2D Registration:
- Solving for 6 or 9 DoF using normalized gradient information (NGI) as similarity metric and covariance matrix adaptation-evolution strategy (CMA-ES) optimizer

Step 3. Check for outliers
Technical Approach - 1. Initialization

i = 1 (first projection)
- Coarse estimation based on geometry: \( T_{d,z} \) and \( T_{s,z} \) are initialized as object-detector distance and detector-source distance
- For orientation, use brute force (rotate 90° about the 3 cardinal axes) to check for all possible 24 orientations and select whichever yielded maximum similarity as \( PM_1 \).

i = 2 (second projection)
- Initialized using \( PM_1 \)

i > 2
- \( PM_{\text{predict}} \) is based on the geometries of the previous two views

\[
\begin{align*}
  d^{i-1}T_{d,i-2} &= d^{i-1}T_{CT}(d^{i-2}T_{CT})^{-1}.

  d^iT_{CT} &= d^{i-1}T_{d,i-2}^{-1}(d^{i-1}T_{CT}),
\end{align*}
\]

: Taken as initialization for \( i \)th view
Technical Approach - 2. 3D-2D Image Registration

- Based on work of Otake et al (2012, 2013)

- Incorporates **normalized gradient information (NGI)** as a robust similarity metric within the covariance matrix adaptation-evolution strategy (CMA-ES) optimizer

- **Similarity(NGI)** between CT ($I_M$) and 2D projection ($I_F$)

\[
T_s, T_d, R_d = \max_{T_s, R_d, R_d \in \mathbb{R}^3} \text{NGI}(I_F, I_M(T_s, T_d, R_d)).
\]

- PM is composed in this way:

\[
PM := \begin{pmatrix}
T_{s,z} & 0 & T_{s,x} & 0 \\
0 & T_{s,z} & T_{s,y} & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
R_{3 \times 3}(R_{d,x}, R_{d,y}, R_{d,z}) \\
T_{d,x} \\
T_{d,y} \\
T_{d,z}
\end{pmatrix},
\]

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

*3D-2D registration is performed for either 6 or 9 DoF.
An assumption that the source position ($T_s$) is fixed with respect to the detector reduces the system geometry from 9 DoF to 6 DoF.
Experimental Method - Overview

- **Experiment 1**: Cylinder phantom on imaging bench
- **Experiment 2**: Anthropomorphic head phantom on imaging bench
- **Experiment 3**: Anthropomorphic head phantom on robotic C-arm
- **Experiment 4**: non-circular orbit

**Performance Evaluation Criterions**
- Full-width at half maximum (FWHM) of a point spread function (PSF) (measured from the tungsten wire in each phantom) for spatial resolution evaluation
- Reprojection error (RPE) associated with the position of the lead BB on the surface of both phantoms
- Quality of 3D image reconstructions in terms of blur, noise, and artifacts (e.g. streak artifacts and distortion of high contrast details)
Results - 1. Spatial Resolution (FWHM of the PSF)

<table>
<thead>
<tr>
<th></th>
<th>EXP 1 (mm)</th>
<th>EXP 2 (mm)</th>
<th>EXP 3 (mm)</th>
<th>EXP 4 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>0.67</td>
<td>0.86</td>
<td>0.73</td>
<td>0.74</td>
</tr>
<tr>
<td>6 DoF</td>
<td>0.66</td>
<td>0.65</td>
<td>0.55</td>
<td>0.66</td>
</tr>
<tr>
<td>9 DoF</td>
<td>0.66</td>
<td>0.66</td>
<td>0.56</td>
<td>0.66</td>
</tr>
</tbody>
</table>

- Exp 1 has similar results.
- Exp 2 and 3 shows improvement in FWHM. General shape and intensity of PSF is improved.
Results - 2. RPE

In exp 1, statistically significant improvement in RPE for self-calibration.
In exp 2, 6 DoF self-calibration method shows significant improvement in RPE.
In exp 3, mean and median of RPE values are improved for self-calibration but the difference is not statistically significant.

<table>
<thead>
<tr>
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<th>EXP 1 (mm)</th>
<th>EXP 2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>0.83</td>
<td>0.84</td>
</tr>
<tr>
<td>6 DoF</td>
<td>~0.69</td>
<td>0.61</td>
</tr>
<tr>
<td>9 DoF</td>
<td></td>
<td>0.82</td>
</tr>
</tbody>
</table>

Exp1: Cylindrical phantom + bench
Exp2: Head phantom + bench
Exp3: Head phantom + C-arm
Results - 3. Image Quality

- Exp 2 shows qualitatively accurate reconstruction of the skull image for both reference and self-calibration methods.
- Exp 3 shows noticeable improvement using self-calibration as streak artifact is reduced.
- Exp 4 shows that self-calibration using a saddle orbit (non-circular orbit) has qualitatively identical image reconstruction.
Assessment

Pros:

- Experiments on multiple set-ups using simple object (cylindrical phantom) and complex object (head phantom) on imaging bench and robotic C-arm
- Tested multiple criterions (FWHM, RPE, image quality)
- Shows feasibility of geometric calibration on non-circular orbits

Cons:

- Image quality does not include quantitative supports.
- No mention of run-time for a complete scan.
- Refer to other paper for explanation (e.g. 3D-2D image registration), only listing of equations.
Conclusion

- Good possible method for 3D-2D image registration for one of our maximum deliverable in our project

- Applicable to our project since our C-arm can make oblique movements with non-circular trajectories.
Questions?