Checkpoint Presentation: Computer-Guided X-Ray C-arm Positioning

03/24/16
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Project Background: Motivation

**C-arm**: An X-ray imaging device with flexible positioning of X-ray source.

- Widely used for diagnostic imaging or surgical procedures in many areas including orthopedic surgeries.

- Multiple degrees of freedom (DOF) of the arm with angular and orbital movements allow guidance and localization for surgeons to set an optimal viewpoint

**Challenge**: “Fluoro-hunting”

- Surgeons should take multiple to set an optimal fluoroscopic view.

- Time-consuming, more radiation exposure to both patients and physicians, physically cumbersome, safety issues.
Project Background: Solution

Goals: Develop user-friendly interfaces to find an optimal C-arm position with a digitally reconstructed radiograph (DRR) generated from preoperative 3D CT data.

Advantages:
- Less time consuming
- Less radiation exposure for both physicians and patients
- Less user variability, more consistency

2 Approaches: Computer interface / Physical interface
1. **Computer Interface (CI)**

- C-arm Source and Center of Rotation Positions
- C-arm Calibration/Registration (C-arm 3D → Optical 3D)
  - Pt. Fiducial
  - Pt-CT Registration (Optical 3D → CT 3D)
- Fluoro-Sim Module

   - Move C-arm source position in simulation
   - Generate DRR
   - Take Fluoro Image
   - Drive C-arm using SITA
   - Evaluation

Advantages of CI
- Less physically cumbersome
- Motorized movement of C-Arm to the desired position

2. **Physical Interface (PI)**

- C-arm Source and Center of Rotation Positions
- C-arm Calibration/Registration (C-arm 3D → Optical 3D)
  - Pt. Fiducial
  - Pt-CT Registration (Optical 3D → CT 3D)
- Fluoro-Sim Module

   - Manually Drive C-arm without radiation exposure
   - Generate DRR
   - Evaluation

Advantages of PI
- Seamless integration to surgery workflow
Original Deliverables

MIN
- Registration of C-arm, patient, and patient CT data with an optical tracker/markers
  - Verification: measure Target Registration Error (TRE)
- Modify existing DRR generation module to define source position i/t/o orbital/angular position

EXP
- Physical Interface: acquire physical C-arm position and display DRR
- Computer Interface: define virtual C-arm position and display DRR
  - Validation: measure Projection Distance Error (PDE) between generated DRR and actual fluoroscopic image

MAX
- Physical/Computer Interfaces:
  - Encoder-based C-arm positioning, Pt-CT reg. w/ 3D-2D image registration
- Computer Interface: Drive the C-arm to preferred position with SITA interface
  - Verification: Measure accuracy of C-Arm positioning, TRE.
DRR generation based on C-arm source position
DRR generation based on C-arm source position

Where

\[ T_w^d = \begin{bmatrix} R_d & p_d \\ 0 & 1 \end{bmatrix} \]

Source is defined in detector coordinate as

\[ T_s^d = T_w^d \quad T_w^s = \begin{bmatrix} I \end{bmatrix} \]

Where \( p_s = [u_0 \quad v_0 \quad SDD] \)

Then projection matrix \( P_i \) defined as:

\[ P_i = I_i \cdot T_s^w \]

Where intrinsic/extrinsic matrices \( I_i \) and \( T_s^w \) are:

\[ I_i = \begin{bmatrix} -SDD & 0 & u_0 & 0 \\ 0 & -SDD & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \]

\[ T_s^w = (T_w^d T_s^d)^{-1} = \begin{bmatrix} R_d & R_d \cdot p_s + p_d \\ 0 & 1 \end{bmatrix}^{-1} \]

\[ x_A = T_A^B x_B \]
Registration

<table>
<thead>
<tr>
<th>Geometric Calibration (C-arm) Coordinates</th>
<th>Optical Coordinate</th>
<th>CT Coordinate</th>
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<td>· C-arm center of rotation</td>
<td>· Patient fiducials</td>
<td>· Preoperative 3D CT data</td>
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<td>· Source Position</td>
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C-arm Registration

\[ F_{Carm}^{Optical} : 	ext{C-arm 3D} \rightarrow \text{Optical 3D} \]

Pt.-CT Registration

\[ F_{Optical}^{CT} : \text{Optical 3D} \rightarrow \text{CT 3D} \]
Registration

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C-arm Registration

\[ F_{Carm}^{Optical} : C\text{ arm }3D \rightarrow Optical\text{ 3D} \]

Pt.-CT Registration

\[ F_{Optical}^{CT} : Optical\text{ 3D }\rightarrow CT\text{ 3D} \]
Patient-CT Registration

- Tracked phantom’s 10 fiducial points, already known in 3D CT data, using an optical tracker.
- Utilized TREK’s built-in fiducial registration, existing software from Dr. Siewerdsen’s Lab
- Horn’s method with Quaternion Technique to perform fiducial registration
- Obtained Phantom to CT transformation matrix defined by fiducial registration using an optical tracker.
Patient-CT Registration: Verification

The registration process validated using Fiducal Registration Error (FRE)

Transformation obated from fiducial registration process registers CT and Phantom fiducials with mean FRE = 0.77 mm.

Other validation methods such as Target Registration Error (TRE) should also be explored
Registration

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\[ F_{Carm}^{Optical} : C\text{-}arm\ 3D \rightarrow \text{Optical}\ 3D \]

\[ F_{Optical}^{CT} : \text{Optical}\ 3D \rightarrow CT\ 3D \]
C-arm Registration

Original Plan: use optical marker attached on the C-arm

Issues:
- Limited field of view of optical tracker
- Accurate location of X-ray source

Encoder: provides orbital/angular position, no FOV issues. Could locate sources by calibration

Change of plan:
- Use encoder-based approach (originally a maximum deliverable)
- Take multiple shots of multi-modal markers in different angles, acquire 3D position of the markers in optical/C-arm coordinate
- Calibration step required in prior to registration
C-arm Registration: Calibration

9 DoF 3D-2D registration used to solve for projection matrix.

Images of calibration object taken from angles $i$. Then projection matrix $P_i$ in the given angle $i$ satisfies

$$X_{2d}^i = P_i \cdot X_{3d}$$

To solve for $P_i$, we set

$$z_i = P_i \cdot X_{3d}$$

Where $z_i$ is a 1x3 matrix defined as $X_{2d}^i = \begin{bmatrix} z_1 / z_3 \\ z_2 / z_3 \end{bmatrix}$

Then, we solve for $P_i = \begin{bmatrix} -p_{s,z} & 0 & p_{s,x} \\ 0 & -p_{s,z} & p_{s,y} \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} R_d & R_d p_s + p_d \end{bmatrix}^{-1}$ which has nine parameters:

$$\begin{bmatrix} p_{d,x} & p_{d,y} & p_{d,z} & \theta_{d,x} & \theta_{d,y} & \theta_{d,z} & p_{s,x} & p_{s,y} & p_{s,z} \end{bmatrix}$$

Source position $p_s^i$ for angles $i$ could be computed from the projection matrix.

Center of rotation acquired by fitting a circle on acquired source positions.

C-arm Registration

COR/projection matrices in multiple angles known from calibration

1. Acquire 2D projections of optical markers from varying angles
2. Compute marker position (centroid) in each projection
3. Triangulate 3D position of the markers in C-arm coordinate
4. Obtain optical positions of the markers
5. Define $T_{optical}^{Carm}: 3D \text{ C-arm} \rightarrow 3D \text{ optical}$ using marker based on 3, 4
6. Where $X_{Carm}$ is source position in C-arm coordinate

$$X_{optical} = T_{optical}^{Carm} \cdot X_{Carm}$$

$$X_{CT} = T_{optical}^{CT} \cdot X_{optical}$$

Accurate registration in simulation

Next: work with actual data.
## Updated Deliverables

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Status</th>
<th>Verification</th>
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</thead>
<tbody>
<tr>
<td><strong>Minimum deliverable</strong></td>
<td></td>
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</tr>
<tr>
<td>Registration: CT-Phantom</td>
<td>Completed</td>
<td>In progress</td>
</tr>
<tr>
<td>Registration: C-arm (Encoder-based)</td>
<td>Completed</td>
<td>In progress</td>
</tr>
<tr>
<td>Modify existing DRR generation to describe source position in orbital/angular position</td>
<td>Completed</td>
<td>In progress</td>
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<tr>
<td><strong>Expected deliverable</strong> (expected starting date: 03/28/16)</td>
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<tr>
<td>Physical Interface, capable of acquisition of physical C-arm position and display of DRR</td>
<td>Not yet started</td>
<td>Not yet started</td>
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<tr>
<td>Computer Interface, capable of specifying virtual C-arm position and displaying DRR</td>
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<td>Not yet started</td>
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<tr>
<td><strong>Maximum deliverable</strong></td>
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<td>Pt-CT reg. w/ 3D-2D image registration</td>
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<td>Computer Interface: Drive the C-arm to preferred position with SITA interface</td>
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</table>
Dependencies

A. Equipment Accessibility - resolved
   a. Access to C-arm, optical tracker, optical markers, and 3D phantoms

B. Software/Existing tools - resolved
   a. Necessary softwares for modules, 3D CT data of phantoms.

C. Version Control/Documentation - resolved

D. Safety Training - In progress (Completed by end of this week)

E. Schedule with mentors - resolved

F. Access to the lab - resolved
# Project Timeline (before)

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Date by</th>
<th>Feb</th>
<th>March</th>
<th>April</th>
<th>May</th>
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<tbody>
<tr>
<td>Meeting with Mentors</td>
<td>8</td>
<td>15</td>
<td>22</td>
<td>4</td>
<td>2</td>
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<tr>
<td>Get Resources, finish setup</td>
<td>22</td>
<td>29</td>
<td>28</td>
<td>25</td>
<td>5</td>
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<tr>
<td><strong>Minimum Deliverables</strong></td>
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<td>Get familiar w/ existing softwares</td>
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<td>Implement angular/orbital source movement</td>
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<tr>
<td>Define detector based on source</td>
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<tr>
<td>Apply physical constraints of C-arm movement</td>
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<td>25</td>
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<td>Registration - CT/C-arm, PI-CT</td>
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<td>Verify registration with TRE</td>
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<td>Finalize UI &amp; FluoroSim module</td>
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<td>Verify compliance to the physical constraints</td>
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<td><strong>Expected Deliverables</strong></td>
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<td>Develop Physical Interface</td>
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<td>Acquisition of real-time source position</td>
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<td>Verification: Compare X ray Image with DRR</td>
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<td>Develop Computer Interface</td>
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<td>Digital manipulation of source position</td>
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<td><strong>Maximum Deliverable</strong></td>
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<tr>
<td>Drive C-arm using SITA (Computer Interface)</td>
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<td>Registration:</td>
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<td>3D-2D image patient registration</td>
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<td>Verification</td>
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Upcoming Milestones

- **Physical Interface**
  - Build a bridge so physical movement of C-arm/Source can be tracked and inputted to the module in real-time (by 04/04/16 → 04/11/16)
  - Acquire X-ray image of preferred view, error check with generated DRR (Validation) (by 04/11/16 → 04/18/16)

- **Computer Interface**
  - Read C-arm/Source position with an optimal fluoroscopic preview (by 04/18/16 → 04/25/16)
  - Verification process by comparing a DRR preview to an acquired X-ray image (by 04/25/16)

- **Advanced Features (MAX)**
  - Using SITA interface, allow computer interface to drive C-arm to a desired position. (by 05/02/16)
  - Encoder-based C-arm position measurement (by 05/02/16 → 03/28/16)
  - Pt.-CT registration via 3D-2D registration with 2 X-ray shots (by 05/05/16)
  - Verification process by comparing a DRR preview to an acquired X-ray image (by 05/05/16)
Questions?