3D Megavoltage Tomographic Reconstruction from Portal Imaging for Patient Positioning

*Martin Szegedi*

*Radiological Sciences*

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*UTHSCSA*
Overview

• Motivation
  – Need for accuracy, MV advantages, Patient positioning, Examples of possibilities

• Materials & Methods
  – Test System, Acquisition, Calibration, Reconstruction, Visualization

• Experimental Results
  – Animal cadaver, phantom data

• Clinical Considerations
  – Workflow, Dosimetric considerations

• Conclusion
Motivation

• Radiotherapy – effective method for treating cancer
• 3D conformal & intensity-modulated radiation therapy – new treatment methods that are very accurate (radiation of lesion, sparing healthy tissue)
• Importance of accurate positioning of patient
• Effectiveness of MV CBCT for application with
  – existing equipment
  – patients with implanted high-Z-materials
  – Dose-Guided RT
Traditional RT Process

- Acquire CT scan of patient
- Therapy planning
  - Defining where patient is to be marked/tattooed for alignment
  - Defining target volume
  - Determination of critical structures
  - Calculation of delivery dose

- Positioning of patient on treatment table
  - Same position as for diagnostic CT scan
- Dose delivery
Patient positioning

• Important and critical task to ensure quality of therapy

• Traditional approaches
  1. Matching reference images from planning system with portal images (prior to treatment) using anatomical landmarks
     • Very low contrast images (faint appearance of patient’s anatomy)
     • Relying on only a few images ➔ inaccuracy
     • Time consuming
  2. Fiducial (skin) markers / surface measurement
     • Rely on skin appearance, which changes during treatment (loss of weight and other factors)
Patient positioning

- **The solution**: Mega-Voltage cone-beam CT (MVCT)
- Large number of very low dose images
- Results in 3D data of patient anatomy in the therapy room
- Allows (rigid/non-rigid) registration to CT data (therapy planning)
- Sufficiently represents the bony anatomy
- Based on acquisition/calibration/reconstruction methods known from X-ray C-arm imaging systems
C-Arm Calibration - Example

Figure 1. X-ray Angio system with C-arm gantry used for data acquisition.

Figure 2. X-ray and geometry calibration phantom

Figure 3. Layout of X-ray geometry calibration software.
Patient positioning - Example
Patient positioning - Example
Initial Test-System

- Siemens linear accelerator PRIMUS
- Amorphous silicon (a-Si) EPID with \((40\,\text{cm})^2\) active area \((1024^2\,\text{pix})\)
- Technical data:
  - source – isocenter 100 cm
  - source – EPID 133 cm
- About 200 images (1 deg offset)
- Linac parameters adjusted in order to produce low intensity (down to 0.02 MU per single image)
Functional Block Diagram

- Planning System
- R&V Primeview Syngo RTT
- Image Acquisition
- Reconstruction
- Volume Targeting
- Therapy WS
- Control Console

- CT Images
- Structures
- Beams

- Pixel data
- Dose per image data

Martin Szegedi
Acquisition of Cone Beam CT

- Acquisition of 2D projection images (portal images)
- Need to cover a minimum of $180^\circ + \text{cone/fan angle, } \sim 188^\circ$
- Typically cover a range of $200^\circ$ with one projection per degree: $265^\circ$ to $95^\circ$ (CW)
- So, we acquire redundant information…
- Timing…
Acquisition of Cone Beam CT

• Timing:
  – Higher MU acquisitions required more time -> slower gantry motion
  – Faster FP means higher gantry motion
  – Safety margin is needed to deal with non-smooth gantry motion—the exact amount TBD
  – No interrupt of rotational motion

![Diagram showing the timing of Cone Beam CT acquisition]

- Beam On Aperture: 20 – 30 ms
- Beam Integration for dosimetry & transmit to CC: 100 ms
- FP Readout: 20 ms, 285 ms or 142 ms
- Safety margin for non-smooth gantry motion: ~40 ms
- Total time for acquisition of one projection image
Acquisition of Cone Beam CT

- **Dosimetry:**
  - Maintain a table/curve to convert the requested MU per image to a beam aperture
  - CB dose calibration must be repeated each time machine configuration is changed
Acquisition of Cone Beam CT

• Image Correction:
  – Offset images for MV CB is similar to portal imaging
  – Dead pixel correction is similar to portal imaging
  – Gain images should be acquired over the arc
  – New gain images must be acquired for each SID
Calibration

- Cylindrical calibration phantom

- Steel markers replaced by tungsten markers

- Normal beam intensity mode (no need for low dose)

- Geometry characterized by projection matrices (taking into account
  - sagging of detector relative to isocenter
  - orientation detector-plane
  - source-detector distance
  - image distortion (beam/FP)
Calibration

- Acquisition of calibration images
  - For every projection image (for reconstruction) there must be a corresponding P matrix
  - Missing projections are allowed, as long as, the image to P-matrix correspondence is preserved
  - Calibration is needed for every SID, i.e. a set of P-Matrices for every SID
Calibration

- Reconstructed Volume
  - A cube centered at the center of calibration phantom
  - Placing phantom at machine isocenter means reconstructed volume will be centered at isocenter
  - Accurate placement of phantom is crucial
Geometry Calibration

- Basics of 3D to 2D Projection

\[
\begin{align*}
\tilde{x} &= P\tilde{X} \\
\begin{cases}
\tilde{x} &= [u, v, 1] \\
\tilde{X} &= [x, y, z, 1]
\end{cases}
\end{align*}
\]

\[
P = \begin{bmatrix}
AR \quad AT
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
\alpha_u & \alpha_v & u_0 \\
\beta_u & \beta_v & v_0 \\
0 & 0 & 1
\end{bmatrix}
\]
Geometry Calibration

- Rotate the image acquisition system around the object
- Acquire one image for every angular increment

\[ \vec{x} = P \vec{X} \]

\[ \vec{X} \text{ (voxel)} \]
Reconstruction

• Reconstruction Field-Of-View:
  – In the plane of rotation:
    • A cylindrical region, within which reconstruction quality is good
    • Image quality drops as we get outside of this region
  – Along axis of rotation:
    • Complex region as shown in the example image

• Reconstruction Volume:
  – Arbitrary cube size
  – Arbitrary number of voxels
  – Isotropic reconstruction

\[
\text{Voxel Size} = \frac{\text{Cube Size}}{\text{Number Voxels}}
\]
Reconstruction

- Generalized Feldkamp:
- Dead Pixel Correction
- Gain and offset correction
- $I_0$ and Log conversion
  \[ N(u, v) = -\int \mu(l) dl = -\ln\left(\frac{i(u, v)}{I_0}\right) \]
- Cosine correction
- Sinogram (Parker) Weighting
- Convolution (filtering)
- Back-projection…
Reconstruction

• Cosine correction:

\[ \tilde{R}_\beta(p, \zeta) = R_\beta(p, \zeta) \cos \Omega \]

Figure 1-7. Cosine correction of cone-beam data.
Reconstruction

- Parker Weighting: Extending the trajectory fills the space—but some areas are filled twice, which causes problems.

the window weights for the same rays at opposite sides of the sinogram must be 1
Reconstruction

- Backprojection:
  - For every 3D voxel in the volume...
  - Project the 3D voxel onto the image plane (using P matrix)
  - Take the filtered image value at that point
  - Add that to the voxel intensity
  - Repeat for every 2D projection
Sources of Image Artifacts

• Sources of image artifacts:
  – Poor gain correction $\Rightarrow$ circular artifacts
  – Dead/bad pixels remaining after dead-pixel correction $\Rightarrow$ circular artifacts
  – Poor offset correction $\Rightarrow$ grainy image, i.e. loss of contrast resolution
  – Electronic noise in the panel $\Rightarrow$ grainy image, i.e. loss of contrast resolution
  – Machine geometry out-of-calibration, $\Rightarrow$ streaking artifacts and half-moon shadows around small high-contrast objects
  – Improper positioning of the calibration phantom, $\Rightarrow$ shift of the volume origin from isocenter
Reconstruction

- Modified Feldkamp algorithm (filtered backprojection)
- Taking into account detector sagging (projection matrices)
- Image pre-processing in order to enhance image quality
- Reconstruction volume with isotropic resolution \( (256^3 \text{ or } 512^3) \)
Experimental Results

• Animal cadaver – sheep’s head

• 200 images

• 9 MU total dose

• Air, bone, and soft tissue separable
Experimental Results

- Registration of MVCT to CT volume data
  - Modified MMI (mutual information) approach
  - Center of MVCT already treatment isocenter
  - Output used for table movement
Reconstruction Results

- Dose vs. reconstruction quality comparison

126 MU

10 MU

5 MU
Clinical Workflow

- First treatment day
  - Therapist loads DICOM RT Planning CT
  - Patient Setup
  - Cone Beam Acquisition
  - Reconstruction
  - Volume Targeting
  - Corrective Action if needed

- Second treatment day
  - See above / depending on protocol
Dosimetric Considerations

• 2 – 15 MU for a whole CBCT
  ~ # of image acquisitions
  ~ anatomical characteristics of object

• MU to Gy translation
  – Commercially available TPS
    ≈ 0.75 – 0.9 cGy/MU (head, prostate)
  – Well below 15 cGy

• Relevance
  – Application in high-dose, low fractionation treatments
  – Calculation and recording into overall dose possible.
Positioning Considerations

a)

b)

c)

6 mm

d)
DICOM RT Extensions
Conclusion & Outlook

- New approach of patient positioning for radiotherapy
- Usable in standard linacs without further modification
- Sufficient quality to incorporate soft-tissue resolution
- Mainly software based approach

- Dose-Guided Therapy approaches possible
- Technical modifications to improve image quality
Literature:


Morin O., Megavoltage Cone-Beam CT: System Description and Clinical Applications. Medical Dosimetry, Vol. 31(1) 2006


And many other articles and resources.

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