

WP7 Most likely path (MLP) estimation

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Workpackage 7 scope

- Calorimeter response
- Calorimeter track reconstruction
- Reconstruction of 3D trajectory track vector matching
- 3D stopping power map

Abstract setup of pCT Phantom reconstruction

Beam

- 2D profile at z_B
- xy position
- E
- rate f

Phantom

- 3D Phantom at z_P , probably around isocenter

Detector

- Flat 2D description at z_D
- xy position
- E'
- direction $\phi\theta$
- rate f' , $n' = \int f' dt$

- Beam, Phantom and Detector descriptions to be modeled in software
- Matching of particles at beam and detector position
- Particle path estimation

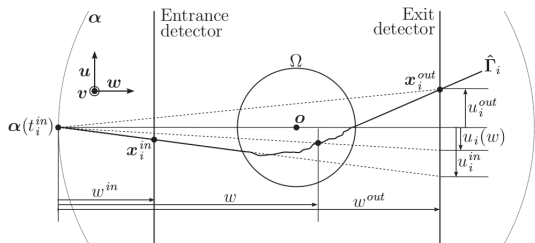
Particle path estimation - Most likely path approach

Reading list:

- R. Schulte et al., *Conceptual design of a proton computed tomography system for applications in proton radiation therapy*, IEEE Trans. Nucl. Sci. 51, 866872 (2004).
- Schulte et al., *A maximum probability proton path formalism for application in proton computed tomography*, Med. Phys. 35, 48494856 (2008).
- D Wang et al., *On the use of a proton path probability map for proton computed tomography reconstruction* (2010)
- S Rit et al., *Filtered backprojection proton CT reconstruction along most likely paths* (2013)

Filtered backprojection along most likely path

- This is the code from Lyon we have
- Cone beam CT setup



- Total energy loss at point in space $\mathbf{x} \in \mathbb{R}^3$

$$-\frac{dE}{dx} = \eta(\mathbf{x})S(I(\mathbf{x}), E(\mathbf{x}))$$

- ▶ η : electron density, S : stopping power, I : ionization potential

- Proton projection integral along path

$$G(E^{in}, E^{out}) = \int_{E^{in}}^{E^{out}} \frac{dE}{S(I_{water}, E)}$$

- ▶ S : stopping power depending on ionization potential I and energy E
- ▶ ionization potential varies moderately in human tissue, take $I(x) \simeq I_{water} = \text{const}$

Making radiograph from data set

- Indicators for a set of spatial indices corresponding to a grid of pixels in plane \perp main axis

$$h_j(\mathbf{y}) = \begin{cases} 1 & \text{if } \mathbf{y} \in \mathbb{R}^2 \text{ is in pixel } j, \\ 0 & \text{else.} \end{cases}$$

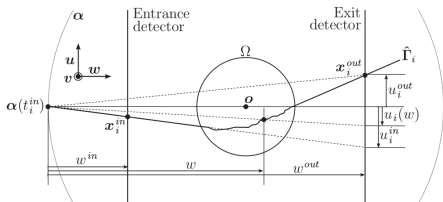
- Histogram for data from N protons from the same source position @ output detector

$$g_j^{out} = \frac{\sum_{i=0}^N h_j(u_i^{out}, v_i^{out}) G(E_i^{in}, E_i^{out})}{\sum_{i=0}^N h_j(u_i^{out}, v_i^{out})}$$

▷ Set of radiographs from multiple source positions is the input to the filtered backprojection algorithm

Generalization

- Histogram for data from N protons from the same source position @ any distance from source



$$g_j(w) = \frac{\sum_{i=0}^N h_j(u_i(w), v_i(w)) G(E_i^{in}, E_i^{out})}{\sum_{i=0}^N h_j(u_i(w), v_i(w))}$$

▷ 3D projection images instead of 2D projection images, the last dimension is related to the distance to the source w

Results - Depth dependence of spatial resolution

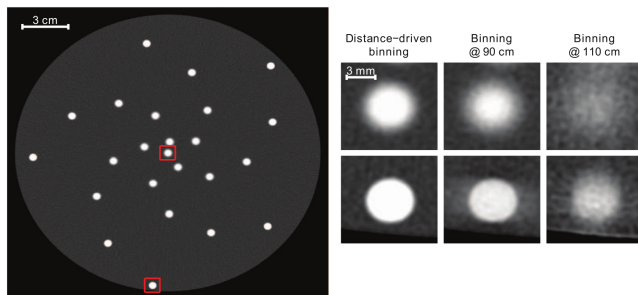


FIG. 3. Simulation 2. Central slice of the pCT reconstruction with distance-driven binning (left) and zooms on the central (right, top line) and peripheric (right, bottom line) inserts indicated with squared boxes. Gray-level range: [0.7, 2]. The first column of zoomed images were obtained with the proposed algorithm and the second and third columns were obtained with the standard FDK algorithm using sinograms binned according to the position of protons at 90 cm (entrance of the phantom) and 110 cm (exit of the phantom) from the source, respectively.

S Rit et al., *Filtered backprojection proton CT reconstruction along most likely paths* (2013)

Results - Spatial resolution of clinical CT scanners

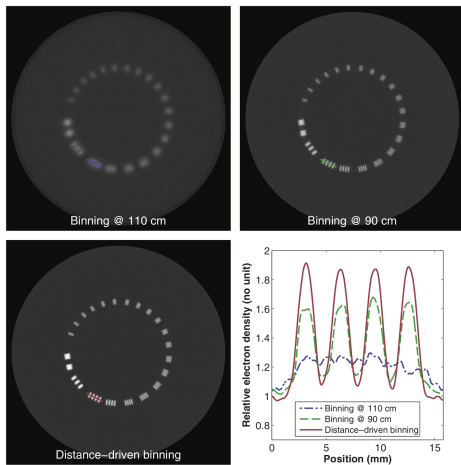


FIG. 4. Simulation 3, full scan. (Top-left) central axial slice of the standard FDK reconstruction using the 2D set of projection images $g(110\text{ cm})$ binned according to the position of protons at the exit of the object. Gray-level range: $[0.7, 2]$. (Top-right) idem with the sinogram $g(90\text{ cm})$ at the entrance of the object. (Bottom-left) distance-driven FDK reconstruction using the complete set of 3D projections g . (Bottom-right) profile along three segments drawn on each slice.

S Rit et al., *Filtered backprojection proton CT reconstruction along most likely paths* (2013)

Use of proton path probability map

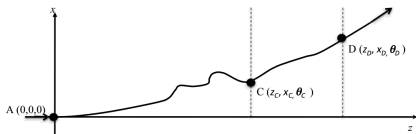


FIG. 2. Illustration of Bayesian inference-based proton path probability estimation. The proton enters at position A and exits at position D. The probability of the proton passing position C is to be estimated.

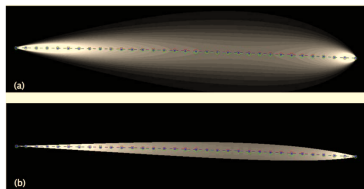


FIG. 5. A typical example of path estimation in 0.25 mm resolution. This path is 24 cm long in its original direction and the lateral deflection is 7.5 mm. (a) Full probability map overlaid with the real path (open squares with dashed line), extracted MLP (stars with dashed line), and CSP (open circles with dashed line); (b) 90% probability path envelope overlaid with the real path (open squares with dashed line), extracted MLP (stars with dashed line), and CSP (open circles with dashed line).

D Wang et al., *On the use of a proton path probability map for proton computed tomography reconstruction* (2010)

comprehensive mathematical description to extract the probability map and most likely path

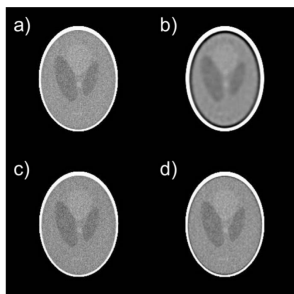
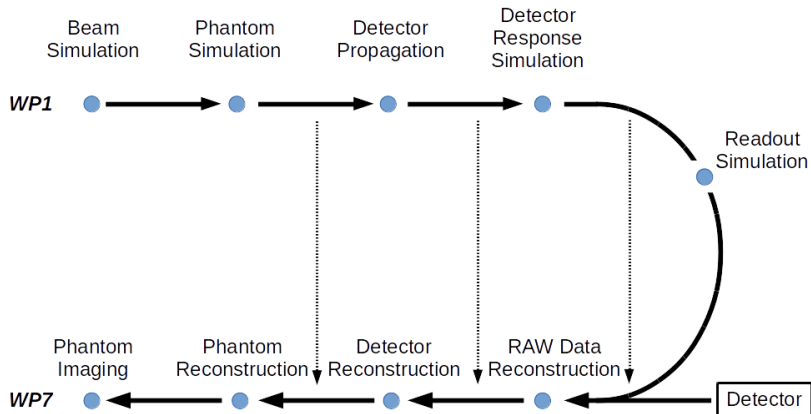


FIG. 6. Reconstruction of pCT using different proton path estimations. (a) One slice of a pCT image of the Shepp-Logan phantom reconstructed using CSP with bilinear interpolation; (b) the same slice reconstructed using the full probability map; (c) the same slice reconstructed using MLP extracted from the full probability map; (d) the same slice reconstructed using MLP extracted from the 90% probability path envelope.

Software for the Bergen pCT

- Most of the studies have been published
- We have access to some of the code
- Common software tools existing: ITK, RTK
- How to understand and integrate the software?

Software - Task sequence



- Task sequence to be split into separate packages
- What is our data model for the flow of information?
- Shortcuts of the cycle can be used to test tasks individually

Software - next steps and milestones

- We should consider WP1 and WP7 together in the software development.
 - "Theoretical" work:
 - ▶ Setup software packages for the complete cycle
 - ▶ Define requirements and specifications for every package
 - ▶ Define Data model (RAW data, hit/cluster, track, calorimeter data set)
 - Practical work:
 - ▶ Start with a decoder and preliminary visualization for raw data
 - ▶ Geometry modeling in an ITK framework
 - ▶ Get examples in the Lyon code working
 - ▶ ...
- ▷ My personal take/wish: define realistic milestones for the next three months