Joint ToF Image Denoising and Registration with a CT Surface in Radiation Therapy

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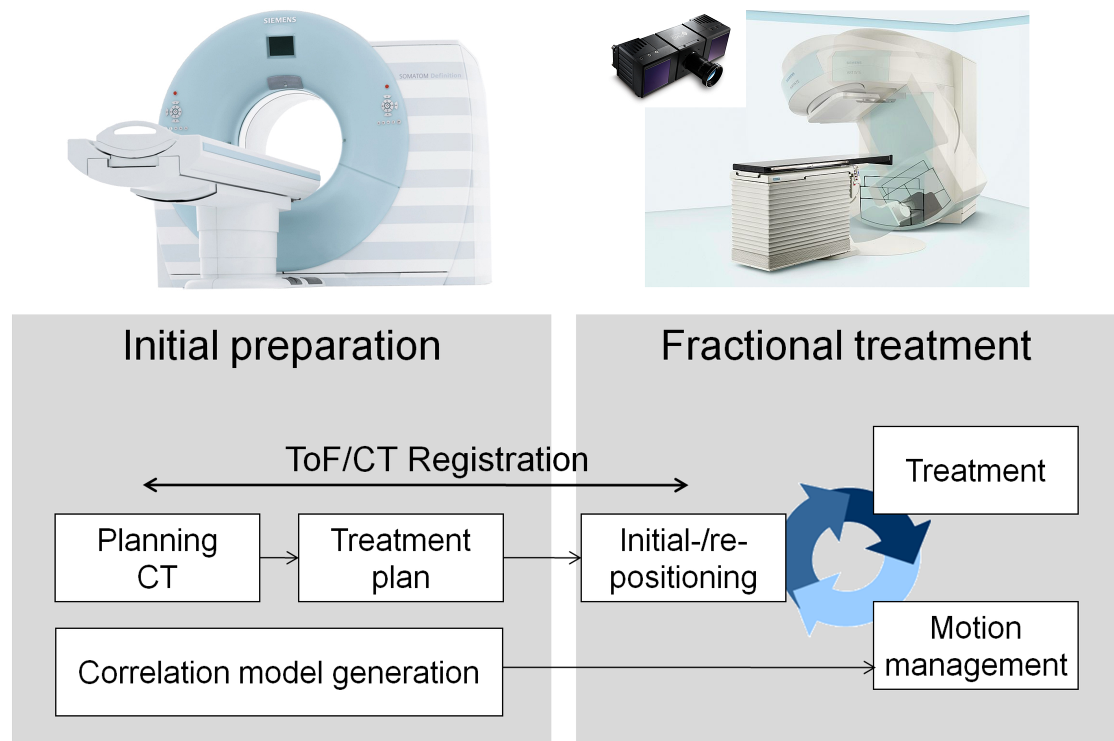
Respiratory Motion Management

- **Challenge:** Management of intra-fractional respiratory motion in radiation therapy → essential for patients with thoracic, abdominal and pelvic tumors
- **Continuous model-based tumor tracking:**
  (1) Continuous tracking of the non-rigid patient surface deformation w.r.t. planning CT
  (2) Correlation with a previously learned respiration model (surface/tumor relationship)
- **Data**: Treatment planning: accurate 3D CT data
  Fraction: noisy Time-of-Flight (ToF) range data



- **Goal:** Robust intra-fractional surface acquisition and deformation tracking w.r.t. CT to cope with variations in patient pose and respiratory motion
- **Joint denoising and registration:** Simultaneously solve denoising of ToF range data and its non-rigid registration to a surface extracted from CT data
- **Idea:** Tackling each task would benefit from prior knowledge of the solution of the other task → combine the two highly intertwined tasks of denoising and registration

Variational Framework

- **Fidelity energy for the range function r**

$$\mathcal{E}_{\text{fid}}[r] := \int_\Omega |r - r_0|^2 \,\mathrm{d}\xi$$

$$r_0(\xi) = \frac{\sum_{i=j-m}^{i=j} \chi^i(\xi) r_0^i(\xi)}{\sum_{i=j-m}^{i=j} \chi^i(\xi)}$$

r_0^i: measured range data at time i
χ: reliability indicator

- **Matching energy**

$$\mathcal{E}_{\text{match}}[u,r] := \int_{\mathcal{G}_r} |P(\phi(x)) - \phi(x)|^2 \,\mathrm{d}a := \int_\Omega d(X_r(\xi) + u(\xi))^2 \,\mathrm{d}\xi$$

Pointwise closeness measure:
$P(x) := x - d(x)\nabla d(x)$
$d(x) := \pm\mathrm{dist}(x, \mathcal{G}_{\text{CT}})$

$$\mathcal{E}[u,r] := \mathcal{E}_{\text{fid}}[r] + \kappa\mathcal{E}_{r,\text{reg}}[r] + \lambda\mathcal{E}_{\text{match}}[u,r] + \mu\mathcal{E}_{u,\text{reg}}[u]$$

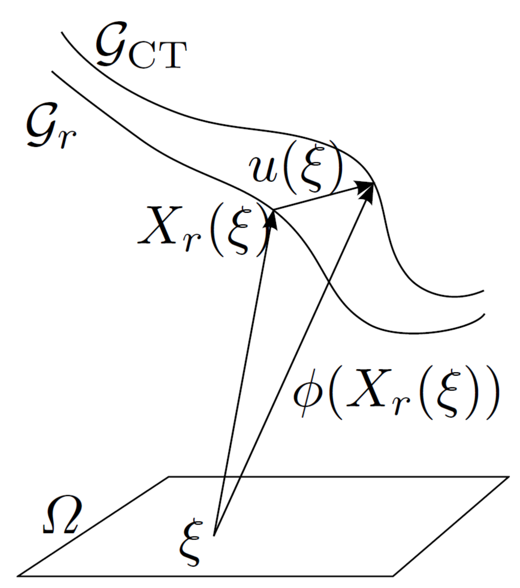
- **Prior for the range function**
  Huber norm approximation (large δ)

$$\mathcal{E}_{r,\text{reg}}[r] := \int_\Omega |\nabla r|_\delta \,\mathrm{d}\xi \qquad |y|_\delta = \sqrt{|y|^2 + \delta^2}$$

- **Prior for the displacement u**

$$\mathcal{E}_{u,\text{reg}}[u] := \int_\Omega |Du(\xi)|^2 \,\mathrm{d}\xi$$

Geometric Configuration



Reliable CT surface: $\mathcal{G}_{\text{CT}} \subset \mathbb{R}^3$

Noise free ToF data: $\mathcal{G}_r \subset \mathbb{R}^3$

Deformation ToF/CT: $\phi(\mathcal{G}_r) \subset \mathcal{G}_{\text{CT}}$

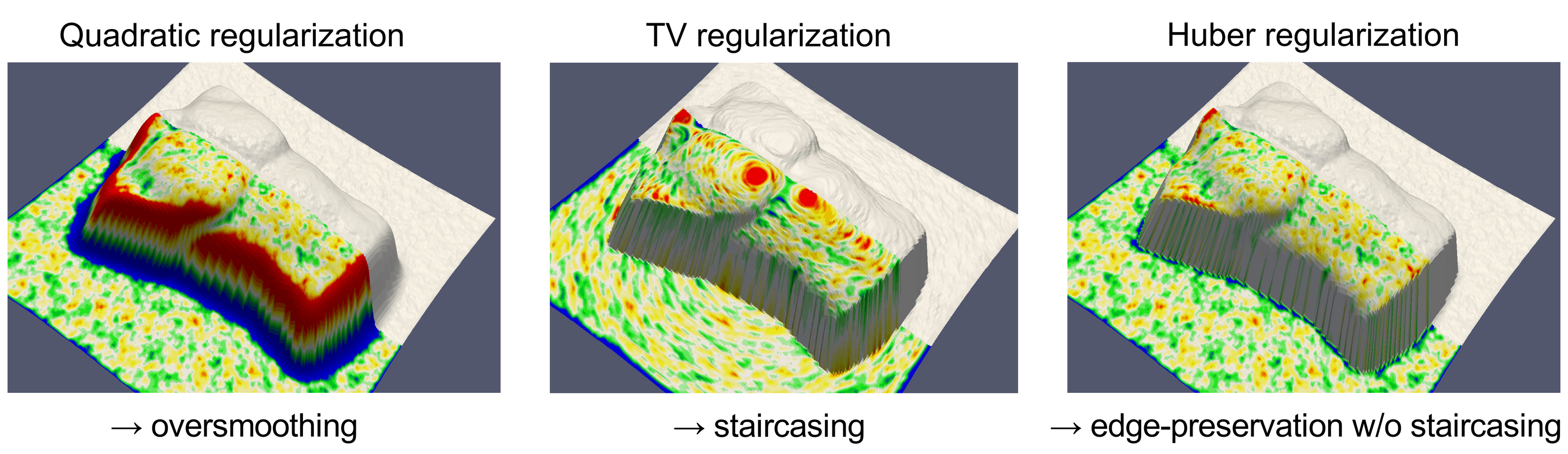
ToF mapping: $X_r(\xi) = r(\xi)\gamma(\xi)$

$$\gamma(\xi) = \left(|\xi|^2 + d_f^2\right)^{-\frac{1}{2}} (\xi_1, \xi_2, d_f)$$

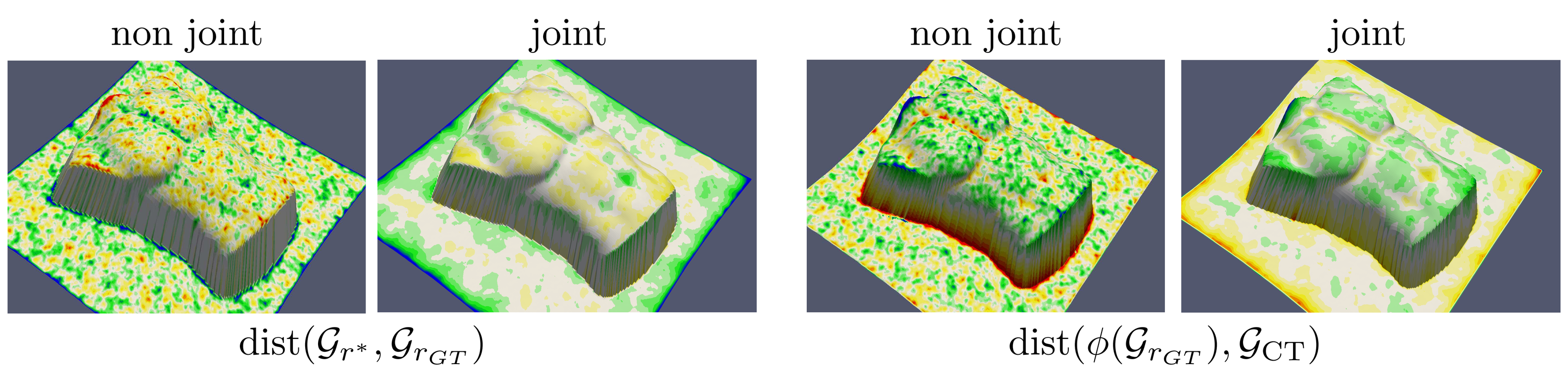
Deformation: $\phi(X_r(\xi)) = X_r(\xi) + u(\xi)$

Experimental Results

- **Huber norm type regularization**

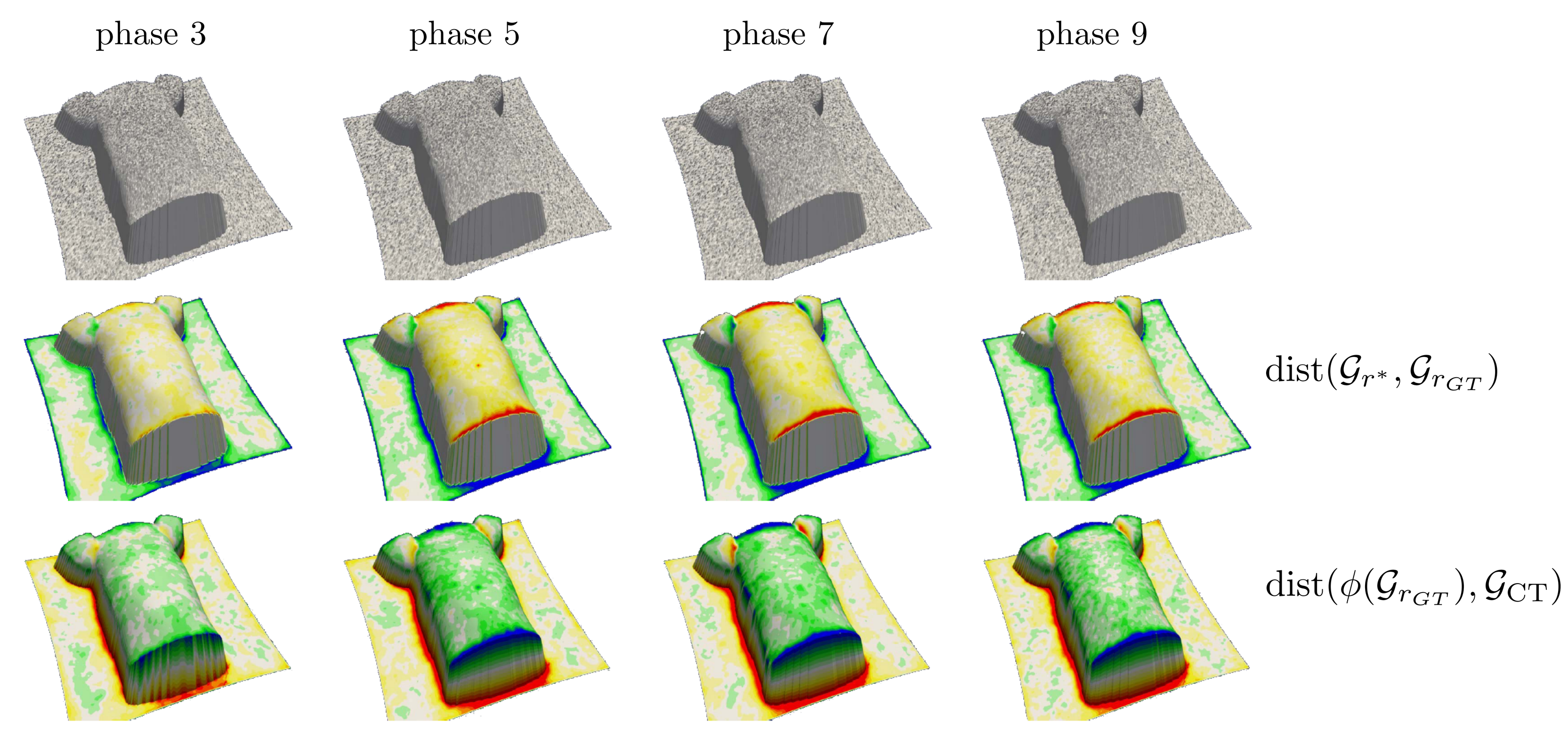


- **Comparison to subsequent denoising and registration**
  → Incorporating prior knowledge about target shape helps denoising
  → Proper denoising renders registration problem more robust



$\mathcal{G}_{r_{GT}}$: Synthetic ground truth range image surface

- **Evaluation with 4D CT respiration phantom (NCAT)**
  - Surfaces from 16 phases within the respiration cycle
  - Synthetic ToF data ($\sigma^2 = 40\text{mm}^2$, time averaging: $m = 5$)
  - Phantom volume at full expiration is considered as CT geometry



- Estimation (r^*, u^*) from previous phase as initial guess for next phase
  → Performance gain (# gradient descent steps): factor 3x

Conclusions

- Case study indicates strong potential for the application in radiation therapy motion management
- Joint approach is capable of significantly reducing systematic errors from ToF imaging
- Outlook: 3D extension of the matching displacement onto the whole geometric model

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