Real-time Respiratory Motion Analysis Using Manifold Ray Casting of Volumetrically Fused Multi-View Range Imaging

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Multi-View Range Imaging (RI)

Motivation
- Incomplete body surface coverage
- Limited sensor field of view (FoV)
- Occlusions by medical equipment

Goals of this work
- Unifying, real-time data fusion
- Continuous surface representation

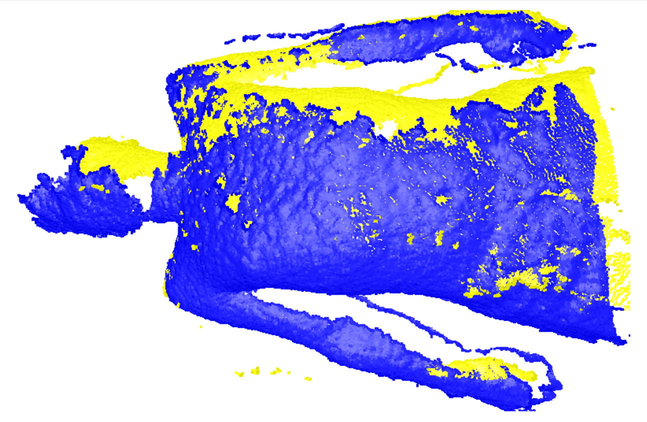

Fig.1: Multi-view RI point cloud data.

RI-based Respiratory Motion Analysis

Applications
- Gating techniques
- Motion compensation

Advantages of RI sensors
- Marker-less, non-intrusive
- No ionizing radiation
- Real-time capable

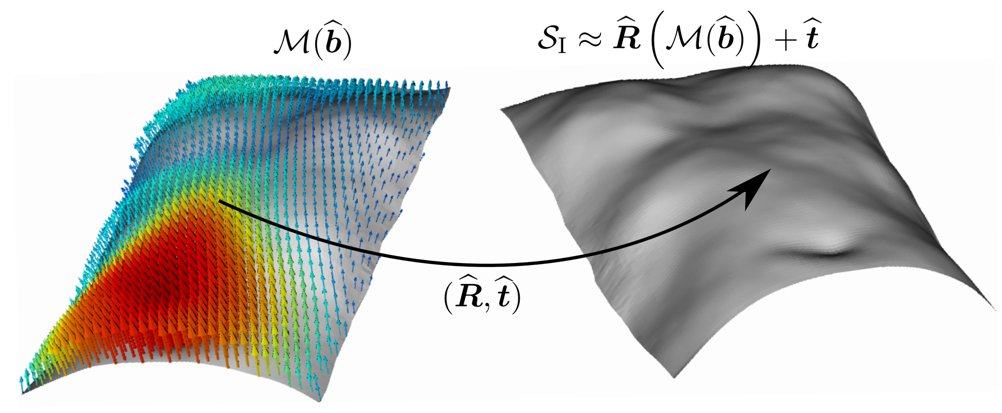

Fig.2: Respiration analysis using 4-D shape priors [1].

Surface Reconstruction Using Manifold Ray Casting of Volumetrically Fused RI Data

Given
- RI surface data $\mathcal{S}_j : \Omega_j \to \mathbb{R}^3$
- Confidence maps $\mathcal{C}_j : \Omega_j \to \mathbb{R}^+$
- Projection operator $\mathcal{P}_j : \mathbb{R}^3 \to \Omega_j$

Implicit Surface Encoding
- Signed Distance $\mathcal{T} : \mathbb{R}^3 \to [-1, +1]$
- Projective point-to-surface distance [2]
  $d_{\mathcal{S}_j}(\boldsymbol{p}_j) = \left\|\mathcal{S}_j\left(\mathcal{P}_j\left(\boldsymbol{p}_j\right)\right)\right\|_2 - \left\|\boldsymbol{p}_j\right\|_2$
- Support region η to account for noise
- Fusion scheme for multiple RI sensors

$$\mathcal{T}(\boldsymbol{p}) = \frac{\sum_{j=1}^{J} \mathcal{C}_j\left(\mathcal{P}_j\left(\boldsymbol{p}_j\right)\right) \cdot \eta\left(d_{\mathcal{S}_j}\left(\boldsymbol{p}_j\right)\right)}{\sum_{j=1}^{J} \mathcal{C}_j\left(\mathcal{P}_j\left(\boldsymbol{p}_j\right)\right)}$$

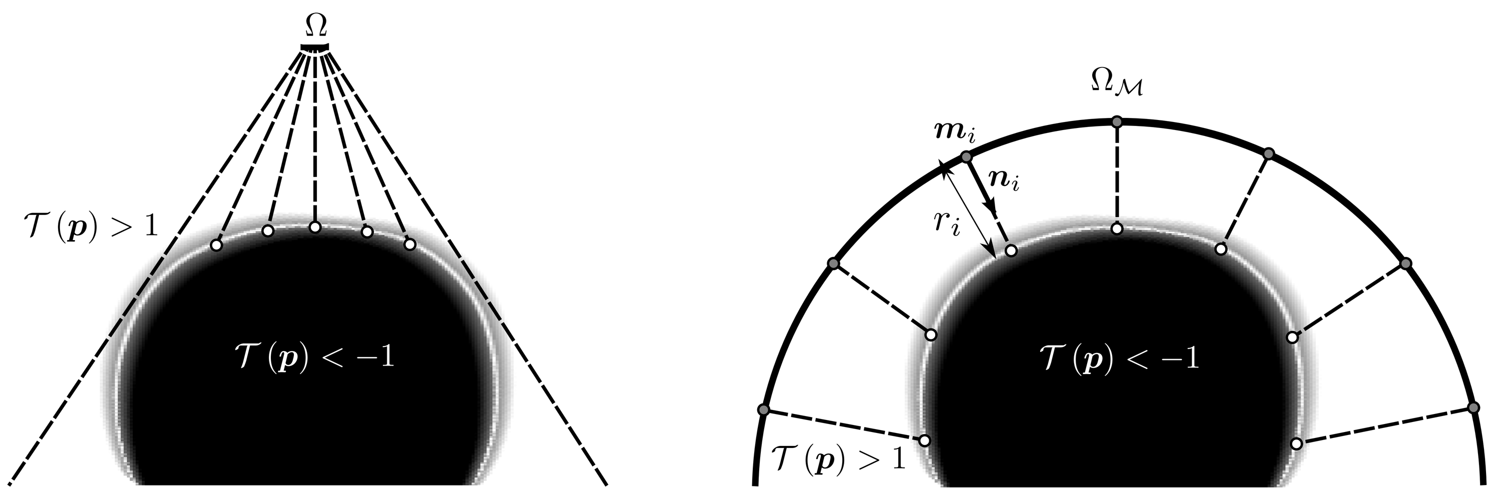

Fig.3: High coverage body surface models. First, multi-view RI data is fused to an implicit surface representation based on signed distance functions (SDF). An explicit surface model is then reconstructed by ray casting the SDF. In contrast to conventional pinhole camera models that do not allow for high surface coverage (*left*) we use a manifold technique to obtain a 180° coverage body surface model (*right*).

Surface Reconstruction Challenges
- Topology with Marching Cubes
- Limited FoV with Pinhole Ray Casting
- 2-D parameterization for performance

Manifold Ray Casting
- RI domain $\Omega_{\mathcal{M}} \subset \mathbb{R}^2$ embedded in $\mathbb{R}^3$
- 2-D parameterization by design
- Viewing rays $\boldsymbol{n_i}$ to emanate throughout the manifold instead of one optical center as with pinhole camera models
- Surface reconstruction
  $\mathcal{T}\left(\boldsymbol{m_i} + r_i \cdot \boldsymbol{n_i}\right) \stackrel{!}{=} 0, \forall \boldsymbol{i} \in \Omega_{\mathcal{M}}$

Respiratory Motion Analysis Using High Coverage Surface Models

Model for RI-based Respiratory Motion Analysis
- Body surface at fixed reference respiration state
  $\mathcal{S}^{\mathcal{F}} = \left\{\boldsymbol{x}_1^{\mathcal{F}}, \ldots, \boldsymbol{x}_N^{\mathcal{F}}\right\},\ \boldsymbol{x}_i^{\mathcal{F}} \in \mathbb{R}^3$
- Elastic deformation field [3] encoding point-wise displacements induced by respiration state k
  $\mathcal{U}^k = \left\{\boldsymbol{u}_1^k, \ldots, \boldsymbol{u}_N^k\right\},\ \boldsymbol{u}_i^k \in \mathbb{R}^3$
- Patient pose and alignment $\boldsymbol{R}^k \in \mathbb{SO}_3, \boldsymbol{t}^k \in \mathbb{R}^3$
- Joint rigid and non-rigid registration
  $\mathcal{S}^k = \left\{\boldsymbol{x}_1^k, \ldots, \boldsymbol{x}_N^k\right\},\ \boldsymbol{x}_i^k = \boldsymbol{R}^k\left(\boldsymbol{x}_i^{\mathcal{F}} + \boldsymbol{u}_i^k\right) + \boldsymbol{t}^k$

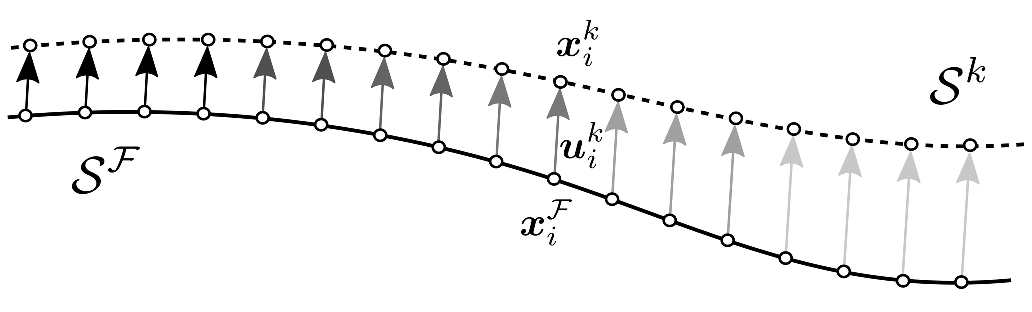

Fig.4: Condition of RI based respiratory motion analysis. For small local surface regions, displacements induced by respiratory motion are hard to be separated from rigid shifts. Increasing the surface coverage allows for a better separation (*cf. color coding w.r.t the magnitude*).

Condition of RI-based Respiratory Motion Analysis
- Concatenated vector notation for deformations
  $\overline{\boldsymbol{u}} = \left(\boldsymbol{u}_{1,x}, \boldsymbol{u}_{1,y}, \boldsymbol{u}_{1,z}, \ldots, \boldsymbol{u}_{N,x}, \boldsymbol{u}_{N,y}, \boldsymbol{u}_{N,z}\right)^{\top} \in \mathbb{R}^{3N}$
- Metric quantifying the linear dependency of deformations and global translations to assess the ability to separate rigid shifts from respiratory motion

$$\mathcal{K}\left(\overline{\boldsymbol{u}}^k\right) = \frac{1}{3}\sum_{i=1}^{3} \frac{\left|\left\langle \overline{\boldsymbol{u}}^k, \overline{\boldsymbol{e}}_i \right\rangle\right|}{\left\|\overline{\boldsymbol{u}}^k\right\|_2 \left\|\overline{\boldsymbol{e}}_i\right\|_2} \in [0, 1]$$

$$\overline{\boldsymbol{e}}_1 = (1, 0, 0, \ldots, 1, 0, 0)^{\top} \in \mathbb{R}^{3N} \ (\text{analogous } \overline{\boldsymbol{e}}_2, \overline{\boldsymbol{e}}_3)$$

Experiments and Results

Data
- 2 Kinect RI sensors (30 Hz, $\Omega_j = \mathbb{R}^{640 \times 480}$)
- Discretization of $\mathcal{T}$ with 512^3 elements
- 4 healthy male subjects S1-S4 with 4 surface coverage regions $\Omega_{\mathcal{M}_i}$
  $\Omega_{\mathcal{M}_4} \subset \Omega_{\mathcal{M}_3} \subset \Omega_{\mathcal{M}_2} \subset \Omega_{\mathcal{M}_1} = \mathbb{R}^{640 \times 480}$
- Motion model [1] with $\left|\mathcal{S}^k\right| \sim 10^4$
  Training: 1 thoracic and 1 abdominal breathing cycle. *Testing:* Regular breathing

Performance Evaluation
- Intel Core i7 3770K, NVIDIA GTX 680
- Fusion and surface reconstruction: 25ms
- Motion model registration: 27ms

Condition of RI -based Respiratory Motion Analysis

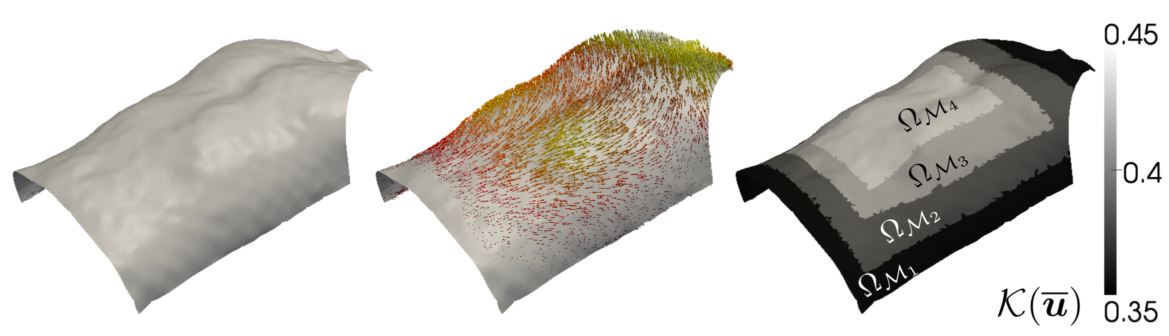

Fig.5: Condition of RI based respiratory motion analysis. Reconstructed surface (*left*) estimated deformation field (*middle*) and the condition for different surface regions (*right*). Note that the proposed metric reflects the surface coverage (*cf.* ***Table 1*** *below*).

	$\Omega_{\mathcal{M}_1}$	$\Omega_{\mathcal{M}_2}$	$\Omega_{\mathcal{M}_3}$	$\Omega_{\mathcal{M}_4}$
S1	0.27	0.30	0.32	0.34
S2	0.27	0.29	0.32	0.34
S3	0.29	0.31	0.33	0.38
S4	0.32	0.34	0.37	0.39

Table 1: Condition metric of body surface deformation fields for subjects S1-S4 and different surface coverage.

Motion Compensated Patient Positioning [1]

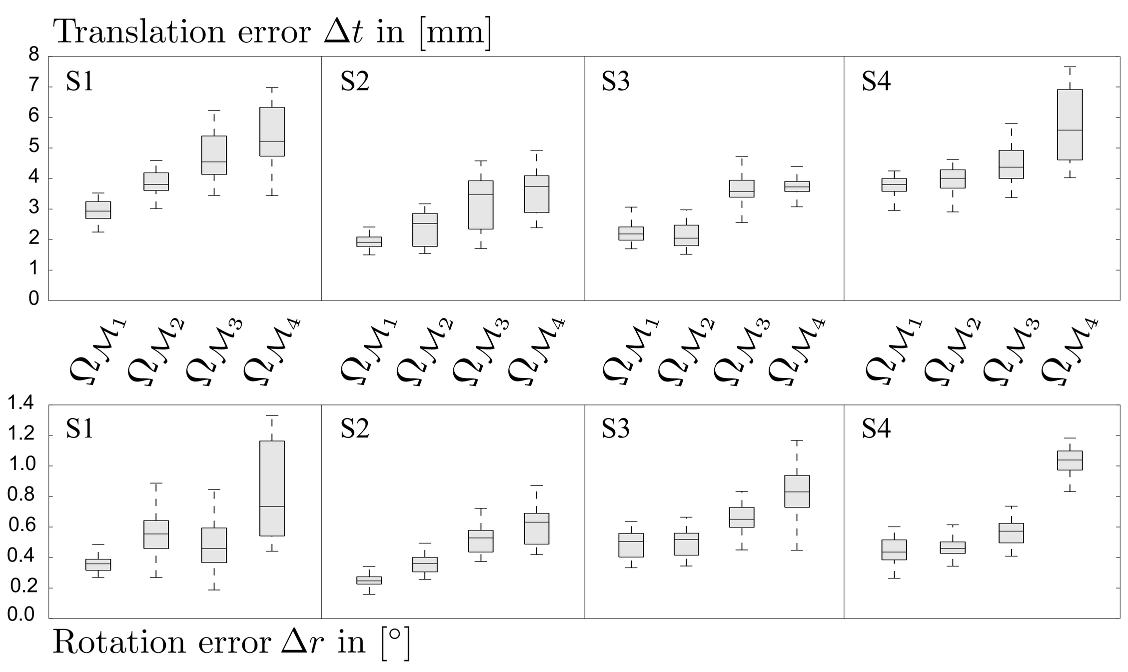

Fig.6: Alignment error in motion compensated positioning for different surface regions. A large body coverage decreases the misalignment (*leftmost element of each quadruple has the largest body coverage*).

Conclusions

- Novel **real-time** framework for high coverage body surface models using **volumetric multi-view RI data fusion** and **manifold ray casting**
- **Condition of RI based surface deformation fields** to quantify the ability to **separate rigid shifts from respiratory motion**
- **Robustness** in patient positioning increased by **high body coverage**

References

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