Real-time Motion Compensated Patient Positioning and Non-rigid Deformation Estimation Using 4-D Shape Priors

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Patient Positioning Using Range Imaging (RI)

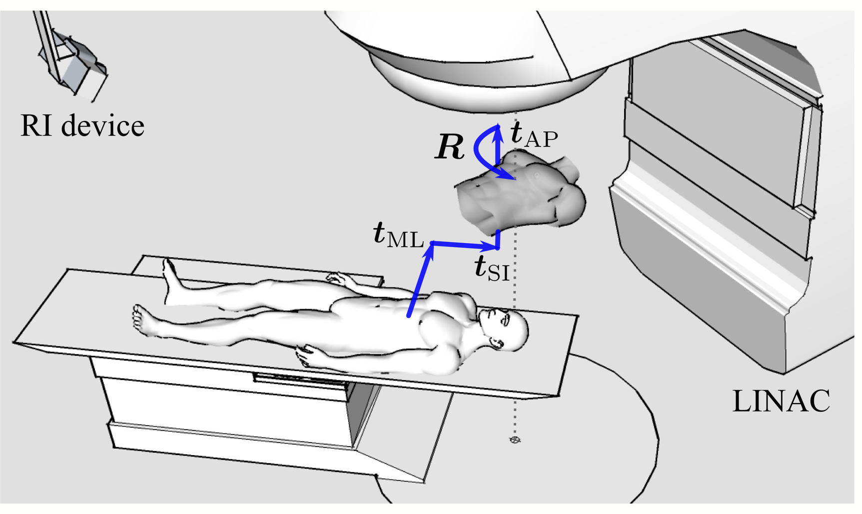

Fig.1: Marker-less patient positioning [2].

Standard Pipeline

- Feature based coarse alignment [1,2]
- ICP for position refinement [1]

Limitations of Existing Systems

- Reference respiration state
- Free-form deformations due to respiratory motion

RI-based Non-rigid Body Surface Registration

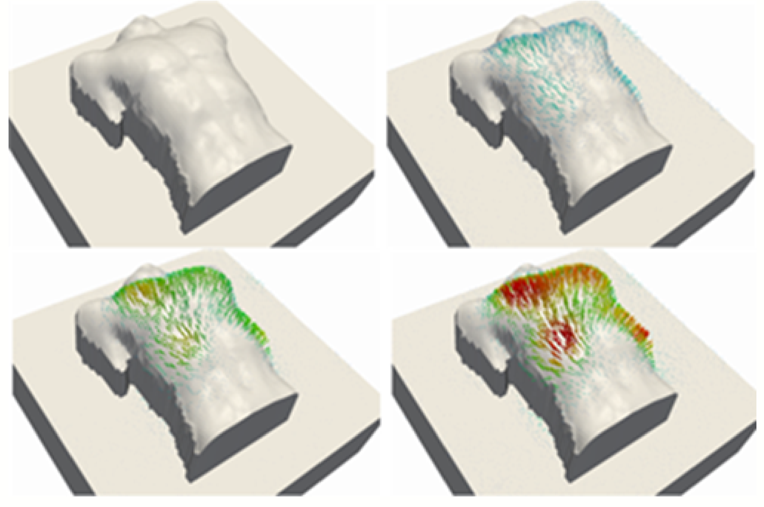

Fig.2: Surface motion fields [3].

Existing Solutions

- Variational formulation [3]
- Non-rigid ICP [4]
- Photometric driven methods

Drawbacks

- Run-times up to several minutes
- Not suitable during interventions due to time constraints

Joint Framework using 4-D Shape Priors

Pre-procedural Workflow

- Acquire RI surfaces $\{\mathcal{S}_1, \ldots, \mathcal{S}_T\}$ at respiration states $t = 1 \ldots T$
- Non-rigid registration to a reference $\mathcal{S}_i \approx \mathcal{S}_{\mathrm{Ref}} + \boldsymbol{u}_i =: \boldsymbol{v}_i$
- Training data $\mathcal{V} = [\mathcal{S}_{\mathrm{Ref}}, \boldsymbol{v}_1, \ldots, \boldsymbol{v}_T]$
- Statistical analysis (PCA) of $\mathcal{V}$ $(\overline{\boldsymbol{v}}, \boldsymbol{\Phi}) = \mathrm{PCA}(\mathcal{V})$
- Model $\mathcal{M}(\boldsymbol{b})$ encoding shape priors $\mathcal{M}(\boldsymbol{b}) = \overline{\boldsymbol{v}} + \boldsymbol{\Phi}\boldsymbol{b}$

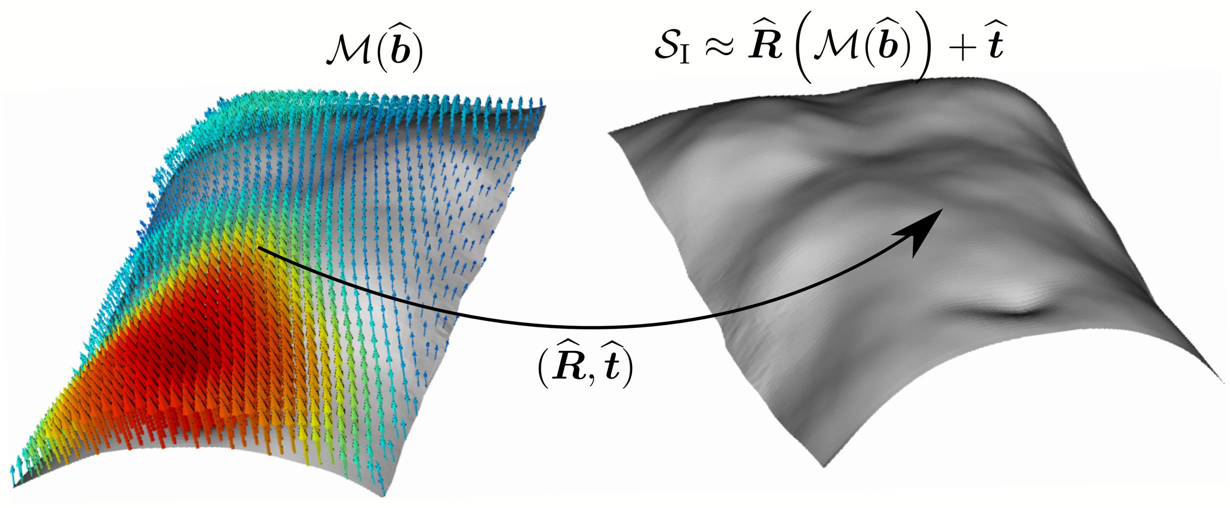

Fig.3: Motion compensated alignment. The reference state (*left gray shape*) is deformed according to $\mathcal{M}(\widehat{\boldsymbol{b}})$ and transformed by $(\widehat{\boldsymbol{R}}, \widehat{\boldsymbol{t}})$ to fit the instantaneous state $\mathcal{S}_{\mathrm{I}}$ (*right*). The displacement field corresponding to $\mathcal{M}(\widehat{\boldsymbol{b}})$ is color coded (*red denotes high, blue low magnitude*).

Intra-procedural Workflow

- Instantaneous surface $\mathcal{S}_{\mathrm{I}}$ and metric d to quantify the distance between two surfaces
- Drive the alignment by the shape priors, simultaneously yielding **(i)** the rigid body table transform (*rotation* $\boldsymbol{R}$, *translation* $\boldsymbol{t}$) and **(ii)** model paramameters $\boldsymbol{b}$ describing respiratory motion
- Objective function $$\widehat{\boldsymbol{R}}, \widehat{\boldsymbol{t}}, \widehat{\boldsymbol{b}} = \underset{\boldsymbol{R},\boldsymbol{t},\boldsymbol{b}}{\mathrm{argmin}}\ d\left(\mathcal{S}_{\mathrm{I}}, \boldsymbol{R}\left(\mathcal{M}(\boldsymbol{b})\right) + \boldsymbol{t}\right)$$

Experiments and Results

Data

- Structured light RI sensor (30 Hz, 640x480 px)
- Training: six subjects S1-S6, one thoracic and one abdominal respiration cycle ($T = 8$ each)
- PCA to explain 99% of the input variance (four modes of variation for each subject)
- Testing: regular breathing over several respiration cylces

Performance Evaluation

- NVIDIA GTX 570 GPU
- CUDA architecture
- Average run-time: 30-40 ms

Motion Compensated Alignment

- Initial alignment error: 10 mm and 5° off from the ground truth
- Our method reduces the alignment error by a factor of 3.0 (*rotation*) and 2.3 (*translation*) compared to conventional ICP

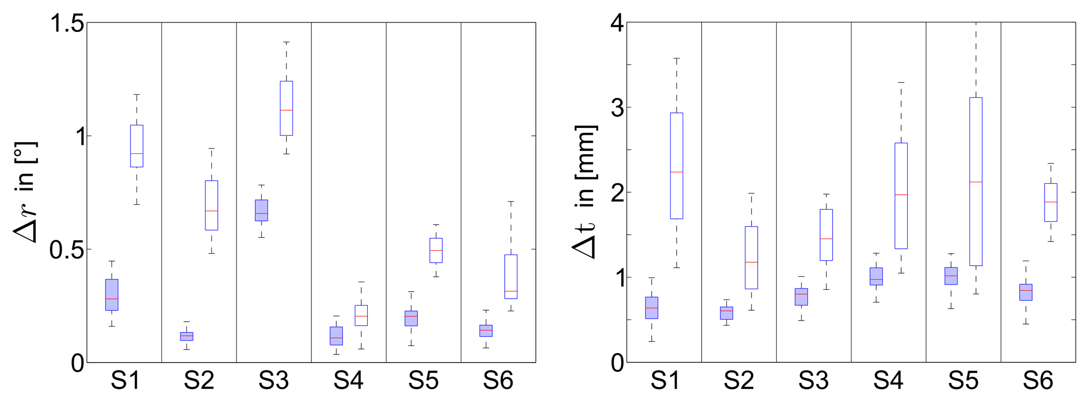

Fig.4: Table transform error of our method (*shaded*) compared to conventional ICP-based alignment (*not shaded*).

Deformation Estimation

- Absolute error in terms of surface mismatch
- Average mismatch ICP: 1.3 mm
- Average mismatch our method: 0.5 mm

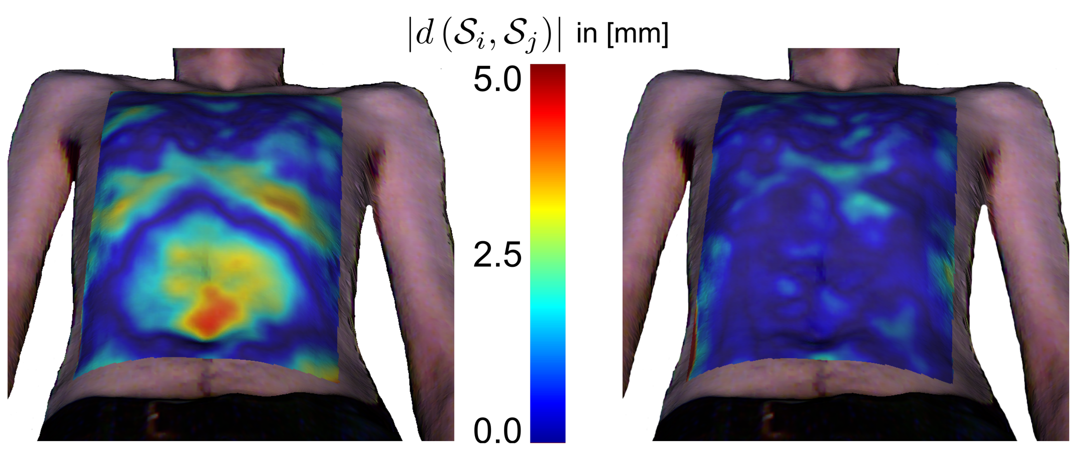

Fig.5: Color coded surface mismatch for ICP-based alignment (*left*) and our method (*right*).

Conclusions

- Incorporating 4-D shape priors for **motion compensated patient positioning** outperforms conventional strategies
- Simultaneous **estimation of surface deformations** enabled by using our method
- **Real-time** capability using off-the-shelf hardware
- **Outlook:** multi-camera setup and volumetric data fusion

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