Intuitive and Smart Editing of 3D Geometrical Heart Valve Models from Cardiac CT Data

Master Thesis Final Presentation

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Outline

- Motivation
- Methods
- Implementation
- Results
- Outlook
- Summarization

Motivation

Fully automatic vs. manual segmentation

- fully automatic detection is not always reliable
- manual segmentation can be very time-consuming

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$\Rightarrow$ Solution: Intuitive and Smart Editing after fully-automatic initialization

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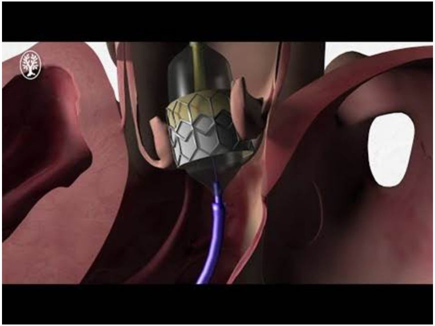
Goals

- efficiency: faster than fully manual modeling
- interactivity: computations should not cause a delay
- intuitiveness: simple to apply, without knowing the mathematics
- robustness: result should be improved after each editing step

3D Geometric Aortic Valve Model

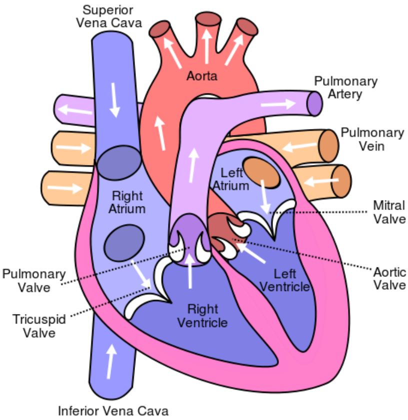
Purpose: diagnosis, surgery and therapy-planning



e.g. Transcatheter Aortic Valve Implantation (TAVI)

Methods

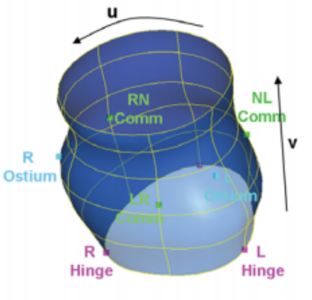
Medical Background: Anatomy of the Heart

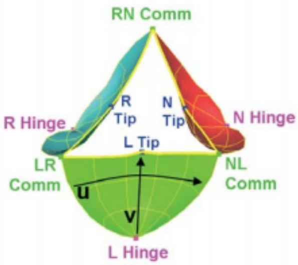


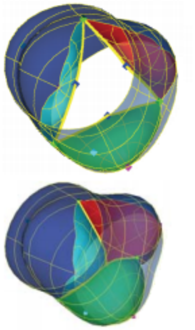
Fully-automatic detection

Hierarchically defined physiological aortic valve model

1. Global location and rigid motion model
2. Nonrigid landmark motion model
3. Surface model







Local Surface Editing

- move one vertex $\boldsymbol{v}_i$ to new position $\boldsymbol{v}'_i$
- vertices $\boldsymbol{v}_j$ in neighborhood are moved in same direction $\boldsymbol{d} = \boldsymbol{v}'_i - \boldsymbol{v}_i$
- moving is damped by influence factor:

$$k_j = \frac{1}{2}(\cos(\pi \frac{\|\boldsymbol{v}_j - \boldsymbol{v}_i\|}{R}) + 1)$$

- moving is damped by angle damping factor:

$$d_j = \cos(\sphericalangle(\boldsymbol{n}_j, \boldsymbol{n}_i)) = \boldsymbol{n}_j \cdot \boldsymbol{n}_i \qquad (\boldsymbol{n}_i \text{ is vertex normal of } \boldsymbol{v}_i)$$

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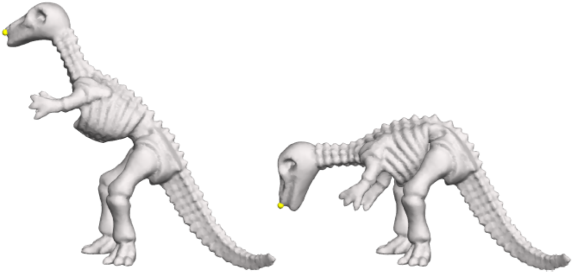
$\Rightarrow$ new vertex positions: $\boldsymbol{v}'_j = \boldsymbol{v}_j + k_j d_j \boldsymbol{d}$

As-Rigid-As-Possible (ARAP) Surface Editing

- fix and move some constraints on the surface
- the remaining, free part of the surface is deformed physically plausible
- the global shape of the surface is preserved



ARAP Surface Editing

- $\mathcal{N}_i$: one-ring neighbors of v_i (all neighbors connected by an edge)
- $\boldsymbol{R}_i$: rotation matrix

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SVD of Covariance matrix: $\boldsymbol{\Sigma}_i = \sum_{j\in\mathcal{N}_i}(\boldsymbol{v}_i - \boldsymbol{v}_j)(\boldsymbol{v}_i' - \boldsymbol{v}_j')^T = \boldsymbol{U}_i\boldsymbol{S}_i\boldsymbol{V}_i^T$

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Best-aligning rotations: $\boldsymbol{R}_i = \boldsymbol{V}_i \boldsymbol{U}_i^T$

ARAP: Objective function

$$\mathrm{E}_{ARAP}(\boldsymbol{V}') = \sum_{i=1}^{|\mathcal{V}|} \sum_{j \in \mathcal{N}_i} \left\| (\boldsymbol{v}'_i - \boldsymbol{v}'_j) - \boldsymbol{R}_i (\boldsymbol{v}_i - \boldsymbol{v}_j) \right\|^2 \rightarrow min$$

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Solve by iterative optimization

1. fix vertex-positions $\boldsymbol{v}'_i$, compute best-aligning rotations $\boldsymbol{R}_i$ (as shown)
2. fix $\boldsymbol{R}_i$, solve for $\boldsymbol{v}'_i$ in sparse linear system:

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$$\boldsymbol{L}\boldsymbol{V}' = \boldsymbol{B}$$

Smooth Energies for ARAP

- problem: artifacts at constrained positions
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- when deformation contains stretching: peaks at constraints

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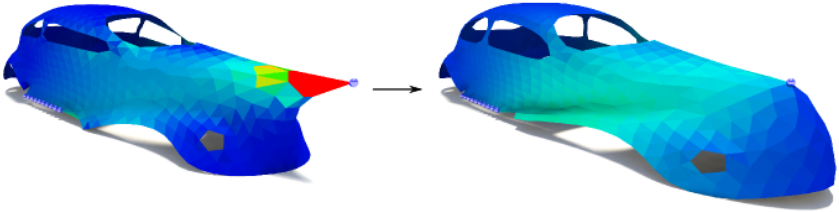
$\Rightarrow$ incorporate energy smoothness



Smooth Energies for ARAP

- minimize energy difference in neighborhood

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Smooth Energies for ARAP

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For one edge $e_k = e_{ij}$: $E_{SMOOTH}(e_{ij}) = (E_{ARAP}(\boldsymbol{v}'_i) - E_{ARAP}(\boldsymbol{v}'_j))^2$

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For all edges: $E_{SMOOTH}(\mathbf{V}') = \sum_{k=1}^{|\mathcal{E}|} E_{SMOOTH}(e_k) \rightarrow min$

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Use regularization parameter β:

$$E_{TOTAL}(\mathbf{V}') = (1 - \beta)E_{ARAP}(\mathbf{V}') + \beta E_{SMOOTH}(\mathbf{V}')$$

Implementation

Implementation

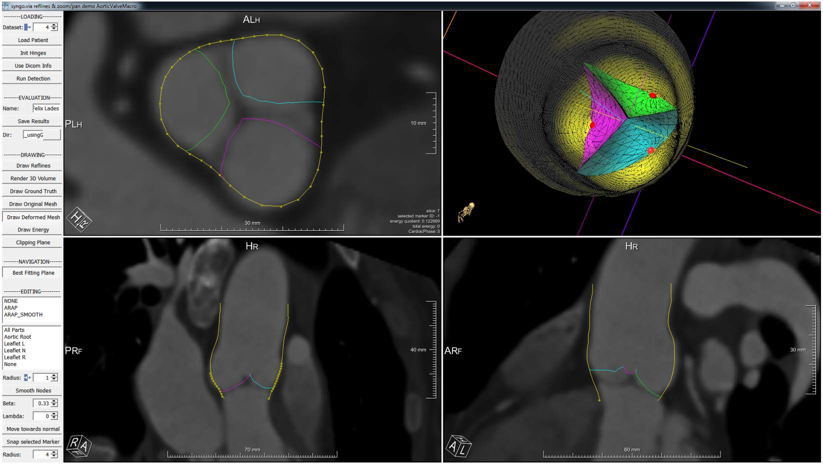
MeVisLab: platform to develop clinical prototypes

- modular C++ interface
- combine algorithms to pipelines and networks
- Open Inventor for interaction and 3D visualization

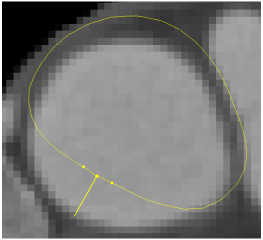
Eigen C++ template library for linear algebra

- Sparse matrix manipulations
- Solving sparse linear systems, e.g. Sparse Cholesky factorization
- SVD

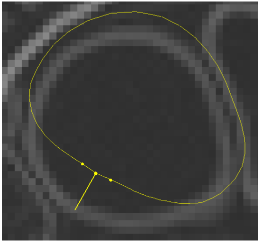
Prototype GUI



Edge snapping



Original image



Gradient image

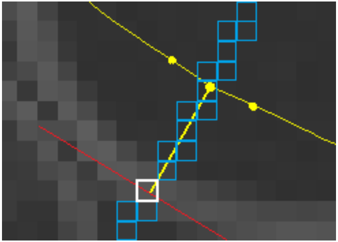
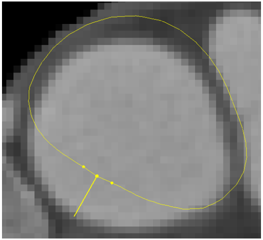


Illustration: voxel sampling

Edge snapping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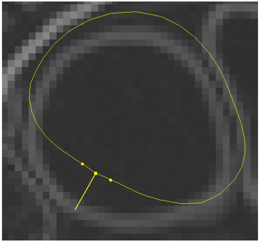
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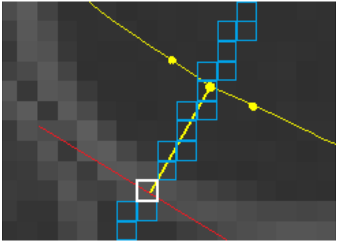
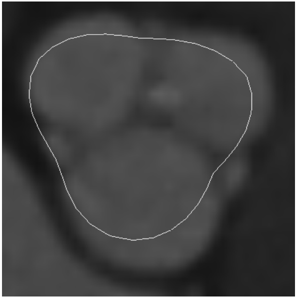


Illustration: voxel sampling

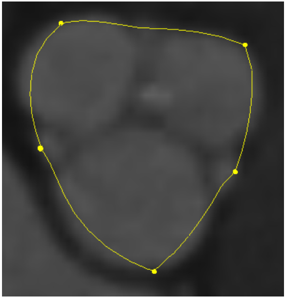
- moved vertex snaps into edge
- here: maximum gradient along moving direction
- highly extendable (e.g. higher level edge detection)

Results

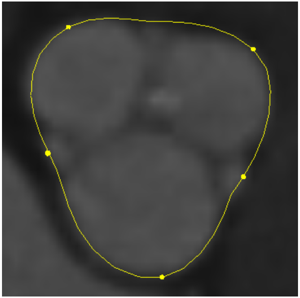
Energy Smoothness Regularization



Initialization with mean shape model



5 constraints, $\beta = 0$



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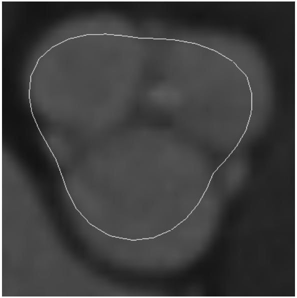

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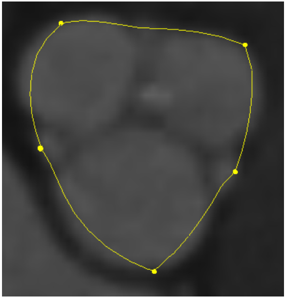

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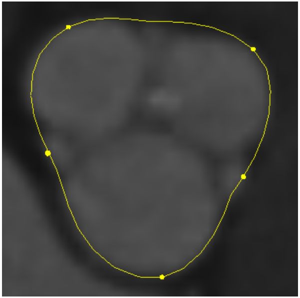

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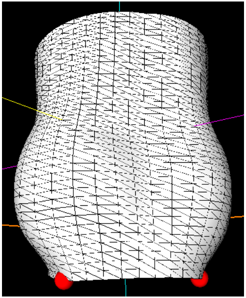
$\Rightarrow$ smoother results with energy smoothness regularization

Energy Smoothness Regularization (energy color-coded)



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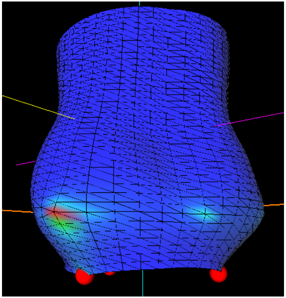

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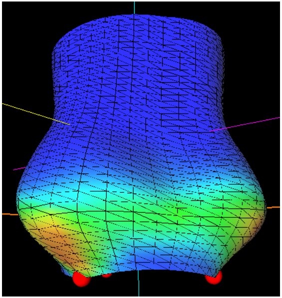

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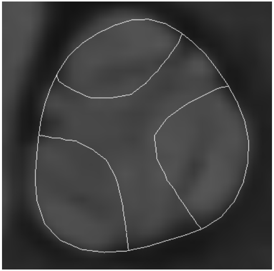
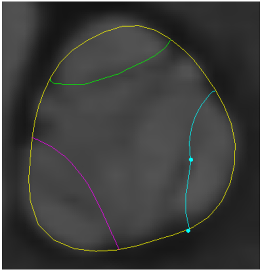
User study: editing of the aortic root

Data set	1	2	3	4	5	6
$d_{avg,init}$ [mm]	**2.21**	**1.13**	**1.05**	**1.68**	**1.39**	**2.43**
$d_{max,init}$ [mm]	6.40	3.41	3.80	4.29	4.43	12.10
$d_{avg,edit}$ [mm]	**0.50** ± 0.07	**0.47** ± 0.05	**0.57** ± 0.04	**0.37** ± 0.03	**0.38** ± 0.02	**0.60** ± 0.15
$d_{max,edit}$ [mm]	2.04 ± 0.08	2.25 ± 0.36	1.82 ± 0.17	1.84 ± 0.06	1.98 ± 0.11	2.43 ± 0.23
$Var_{avg,inter}$ [mm]	**0.41**	**0.47**	**0.37**	**0.37**	**0.37**	**0.60**
$Var_{max,inter}$ [mm]	0.46	0.52	0.41	0.41	0.43	0.79
time [s]	216 ± 89	126 ± 67	134 ± 34	205 ± 74	143 ± 51	416 ± 254
constraints set	47 ± 4	32 ± 12	40 ± 12	82 ± 43	47 ± 15	52 ± 22

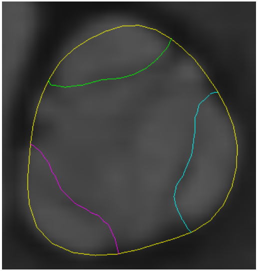
Editing of the aortic leaflets



Initialization



ARAP Editing



Local Editing

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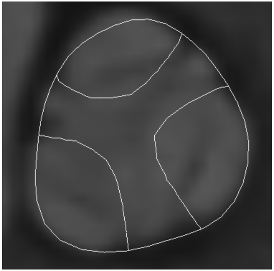

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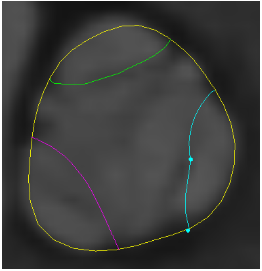

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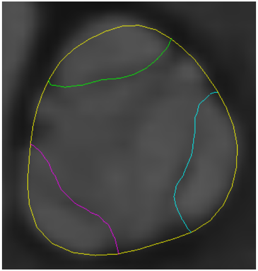
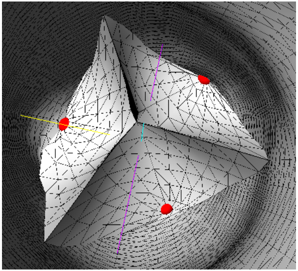


Local Editing

- valve closed after initial fully-automatic detection
- image data shows an open valve
- valve opening as editing step

Editing of the aortic leaflets



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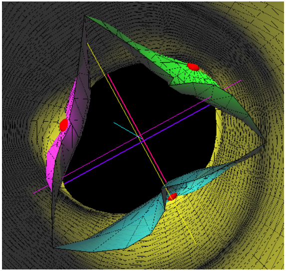

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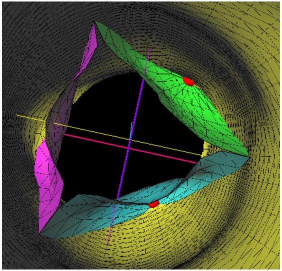

Local Editing

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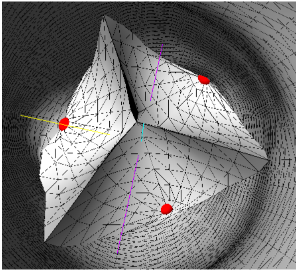

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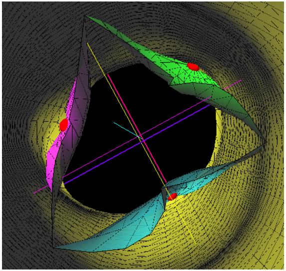

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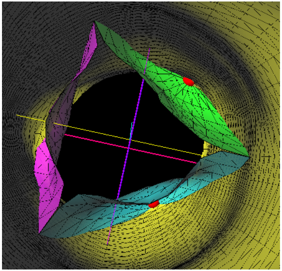

Local Editing

- acute angles at leaflet tip vertices in the middle are detail features
- detail features can not be easily eliminated with ARAP
- better results here with local editing

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Outlook

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Evaluation for …

- …mitral valve editing
- …editing of the right heart valves
- …four-chamber segmentation editing
- …other organs like e.g. the liver

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Snapping and shape validation based on other image features

- Canny edge detector
- features obtained by learning-based methods

Summarization

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Intuitive and Smart Editing after fully-automatic initialization ...

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- ... is a very nice and intuitive approach
- fix and move some constraints on the surface ...
- ... and the remaining, free part is deformed physically plausible
- use energy smoothness regularization for smoother results

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- ...provides a way better accuracy than fully-automatic detection

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Enhance efficiency and accuracy by involving image data (”edge snapping“)

Sources

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Thank you for your attention!