Real-time 3D Segmentation of the Left Ventricle Using Deformable Subdivision Surfaces

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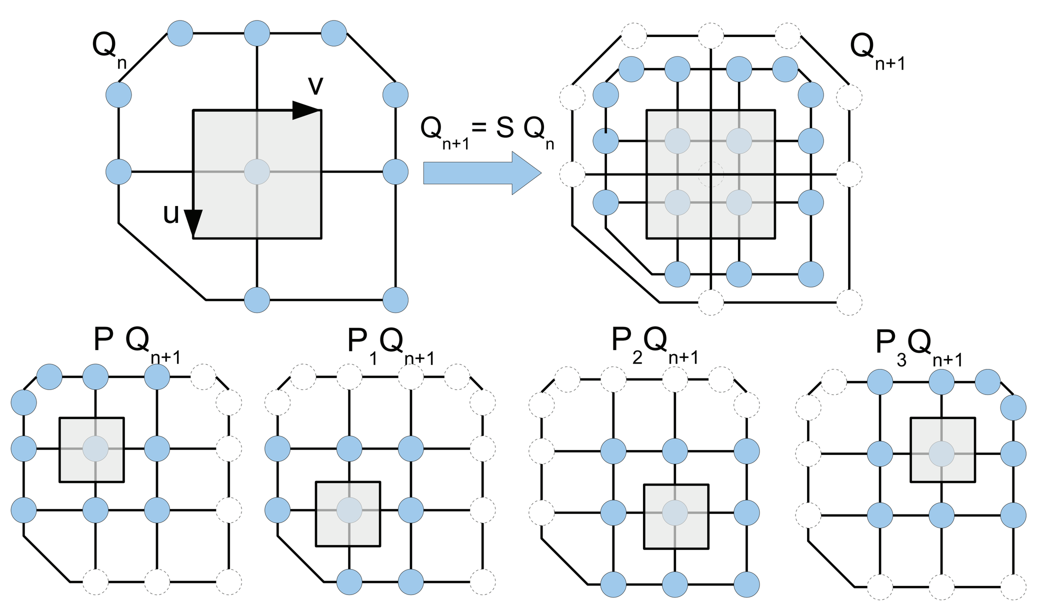
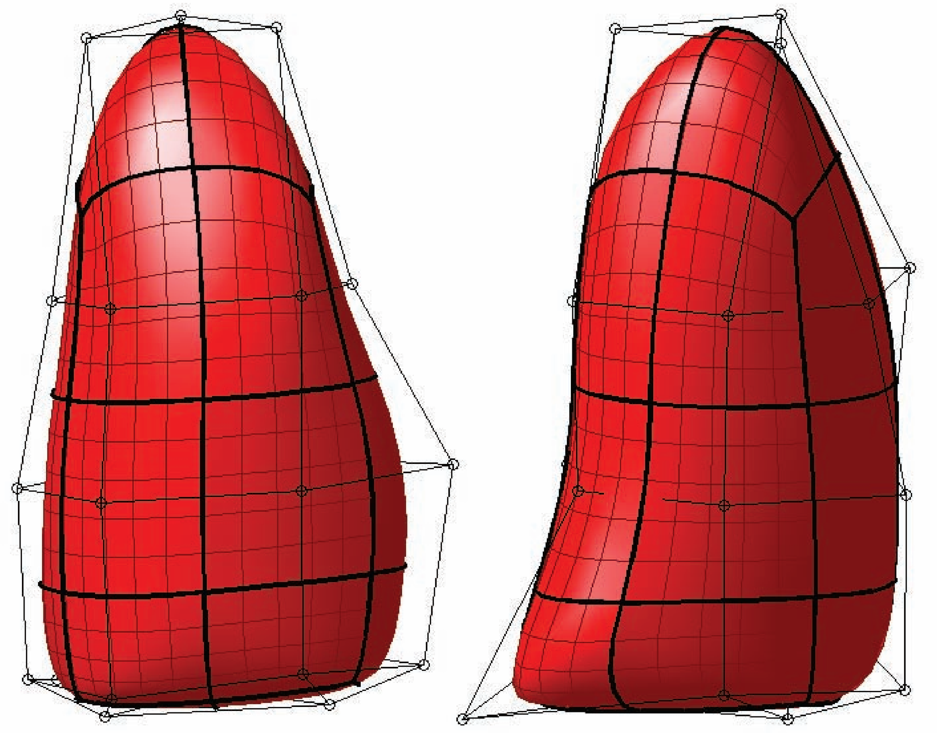
Deformable Subdivision Surface

- Use method of J. Stam to evaluate arbitrary points on subdivision surface:
  - Subdivide mesh recursively until desired point lies within a regular surface patch.
  - Implement subdivision analytically, as a matrix exponential operation.
  - Precalculate basis functions for surface points during tracking initialization.
  - Surface point evaluation can then be performed efficiently (weighted sum).
- Doo-Sabin subdivision surface.
  - Generalizes bi-quadric B-splines to arbitrary topology.
- Control vertices move during tracking to alter shape.
- Global transform to position, scale and orient the model.



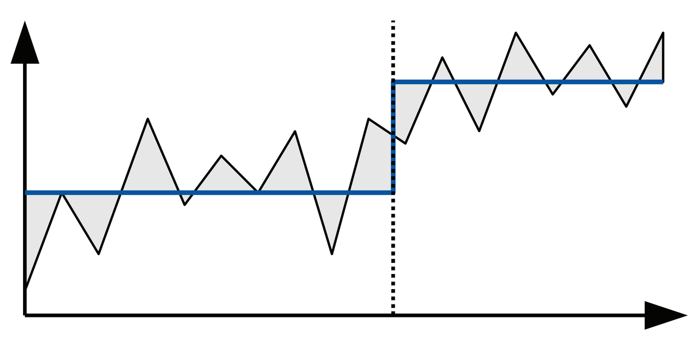
(a) Doo-Sabin subdivision process.



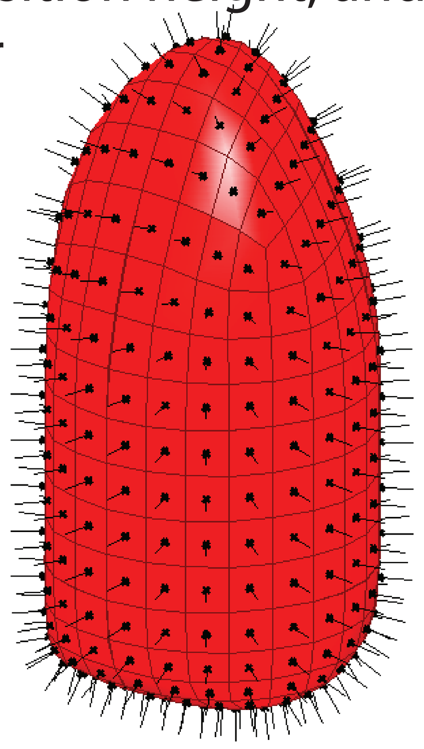
(b) Two views of a fitted subdivision surface, showing red surface patches and control vertices in the encapsulating wire-frame

Edge-detection

- Edge-detection performed in search profiles, distributed evenly over the surface.
  - ~500 profiles, each consisting of 30 samples spaced 1 mm apart.
- "Transition criteria" as edge detector:
  - Least-squares approx. of search profile to detect postion of strongest edge.
  - Robust criteria, with long radius of convergence.
- Weight edges based on transition height, and combine with simple outlier rejection.

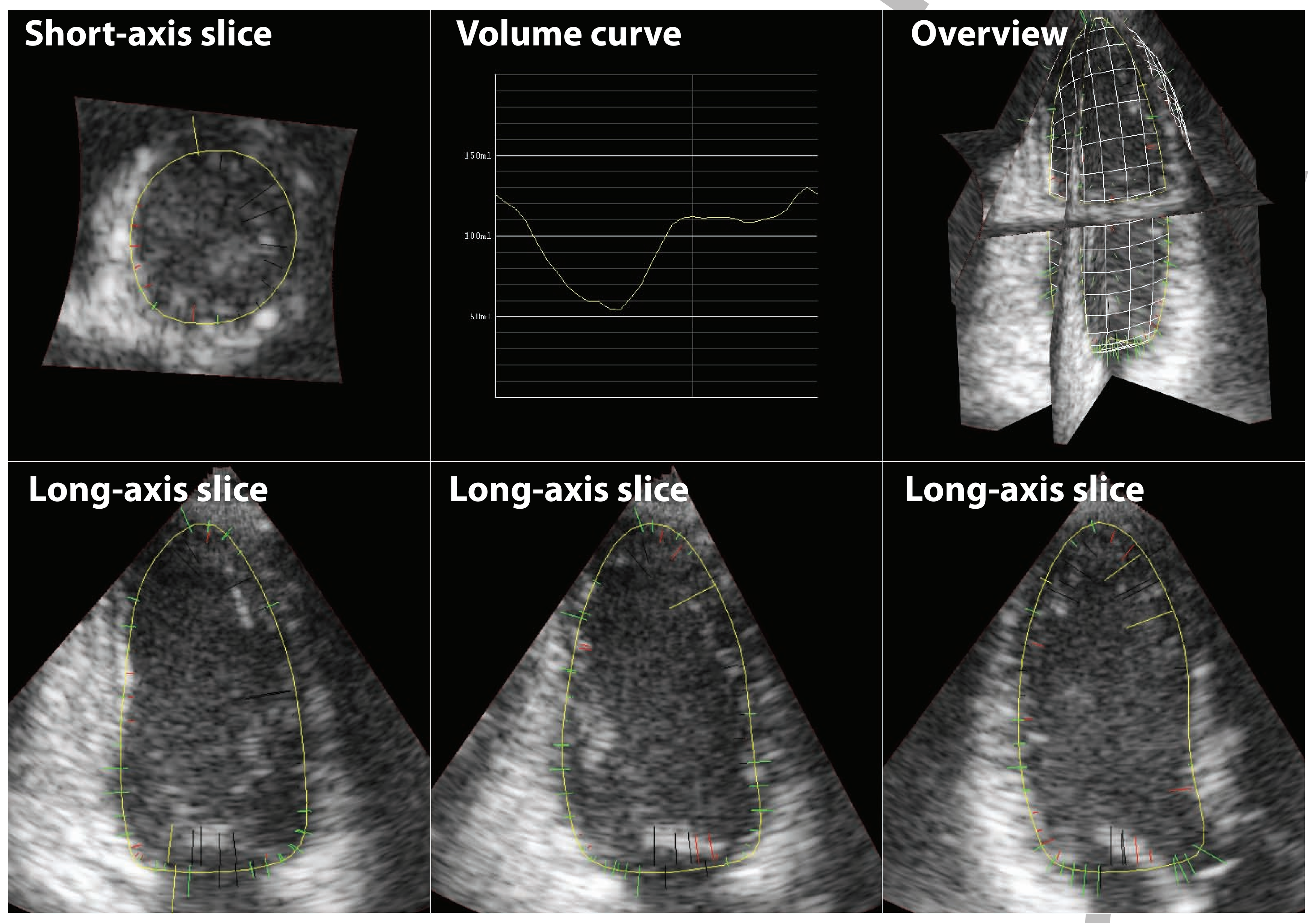


(a) "Transition" edge criteria



(b) Search-profile distribution

Example Screenshot



Screenshot from real-time 3D segmentation in 3D echocardiography

Tracking framework

- State-estimation approach to 3D segmentation.
  - State vector consisting of control vertex positions ($\mathbf{x}_l$) and global transform parameters ($\mathbf{x}_g$):

$$\mathbf{x} \equiv \left[\mathbf{x}_g^T, \mathbf{x}_l^T\right]^T$$

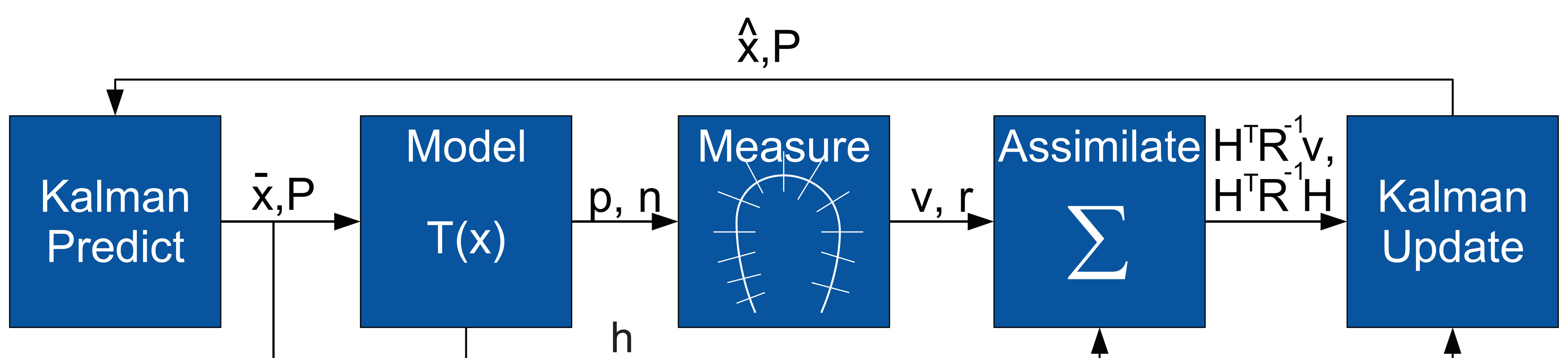
- Use an extended Kalman filter for state estimation:
  1) Kinematic model to predict state vector for each new frame:

$$\bar{\mathbf{x}}_{k+1} - \mathbf{x}_0 = \mathbf{A}_1(\hat{\mathbf{x}}_k - \mathbf{x}_0) + \mathbf{A}_2(\hat{\mathbf{x}}_{k-1} - \mathbf{x}_0)$$

  2) Create a model based on the prediction, and compute surface points.
  - Compute Jacobian matrices ($\mathbf{J}$) for each surface point.

  3) Perform edge-detection along surface normals.
  - Compute normal displacement (v), measurement variance (r) and a measurement vector ($\mathbf{h}$) for each edge:

$$v = \mathbf{n}^T(\mathbf{p}_{obs} - \mathbf{p}) \qquad \mathbf{h}^T = \mathbf{n}^T\mathbf{J}$$



Block diagram over the separate stages in the tracking framework

- Measurement update:
  - Assume independent measurements.
  - Perform outlier removal for edge measurements.
  4) Assimilate edge-detection measurements in information space:

$$\mathbf{H}^T\mathbf{R}^{-1}\mathbf{v} = \textstyle\sum_i \mathbf{h}_i r_i^{-1} v_i$$

$$\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H} = \textstyle\sum_i \mathbf{h}_i r_i^{-1} \mathbf{h}_i^T$$

  5) Fuse measurements with the prediction to compute an updated state estimate:

$$\hat{\mathbf{x}}_k = \bar{\mathbf{x}}_k + \hat{\mathbf{P}}_k \mathbf{H}^T\mathbf{R}^{-1}\mathbf{v}_k$$

$$\hat{\mathbf{P}}_k^{-1} = \bar{\mathbf{P}}_k^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}$$

Results

- From 21 unselected 3D echocardiography recordings (GE Vivid 7 scanner).
  - Tracking initialized by placing the model in the center of the image volume.
- Successful segmentation in all 21 recordings.
- Fully automatic segmentation, without user intervention.
- **25fps segmentation consumes 8% CPU on a 2.16GHz dual-core CPU!**
- Segmented meshes were compared to meshes from a semi-automatic segmentation tool (GE Vingmed):

Distance [mm]	EDV [ml]	ESV [ml]	EF [%]
2.2 ± 0.8	3.6 ± 21.4	9.0 ± 17.4	-5.9 ± 11.1

Table 1. Bland-Altman analysis of the segmentation results compared to the reference segmentation. Results are expressed as mean difference ± 1.96SD.

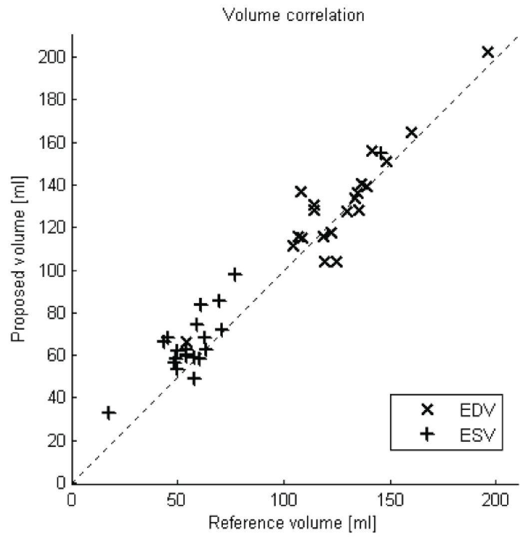


Figure 4. Volume correlation plot for the proposed segmentation against the reference method at end-diastole (EDV) and end-systole (ESV) in each of the 21 recording.

Bland-Altman analysis of mesh distances and volume correspondence

Conclusion

- Real-time 3D segmentation with subdivision surfaces in dense volumetric data is computationally feasible.
- Using a Kalman filter, tracking of the left ventricle can be performed fully automatic, and in real-time.