Real-time Tracking of the Left Ventricle in 3D Echocardiography Using a State Estimation Approach

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Motivation

- The latest generation of ultrasound scanners are capable of acquiring volumetric data in real-time.
- There is a clinical need for automated analysis of 3D ultrasound.
- Accurate real-time segmentation in volumetric data can provide instant feedback and diagnosis during acquisition.

Contribution

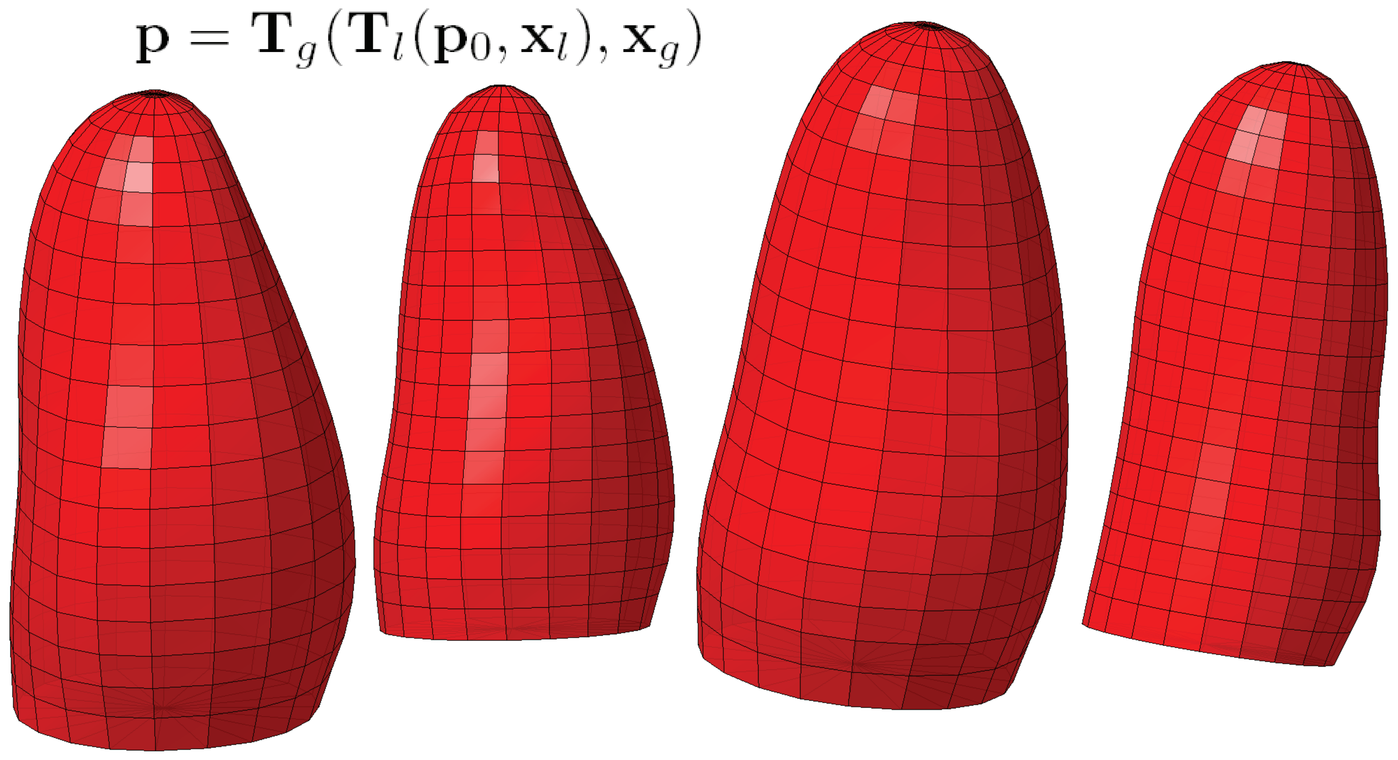
We have demonstrated that:

- Real-time tracking of deformable models in dense volumetric data is computationally feasible.
- Tracking of the left ventricle in 3D echocardiography can be performed fully automatic, and in real-time.

Deformable model

- Bi-quadric B-spline surface.
- 24 control points are allowed to move inwards and outwards during tracking to alter the shape of the model.
- Combine local spline deformations (T_l) with a global transform (T_g) to position, scale and orient the model:

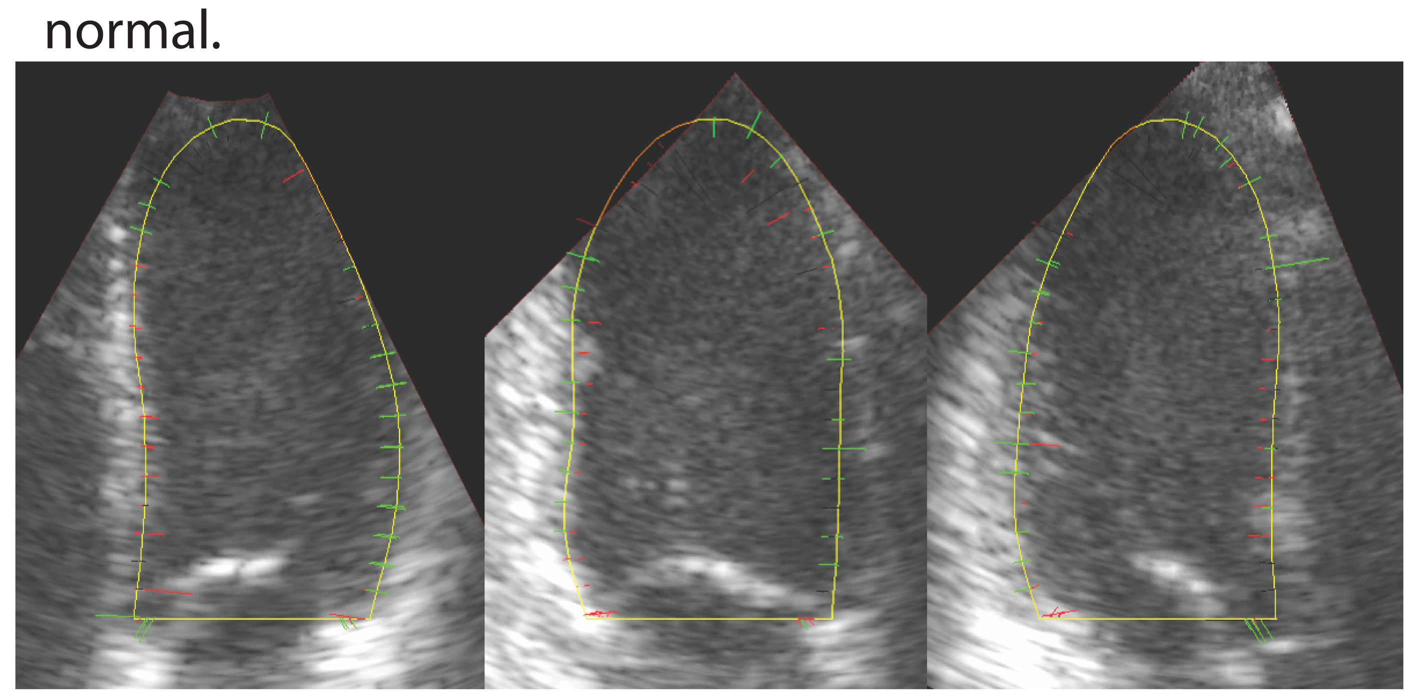
$$\mathbf{p} = \mathbf{T}_g(\mathbf{T}_l(\mathbf{p}_0, \mathbf{x}_l), \mathbf{x}_g)$$



End-diastolic and end-systolic meshes from two of the recordings

Edge-detection

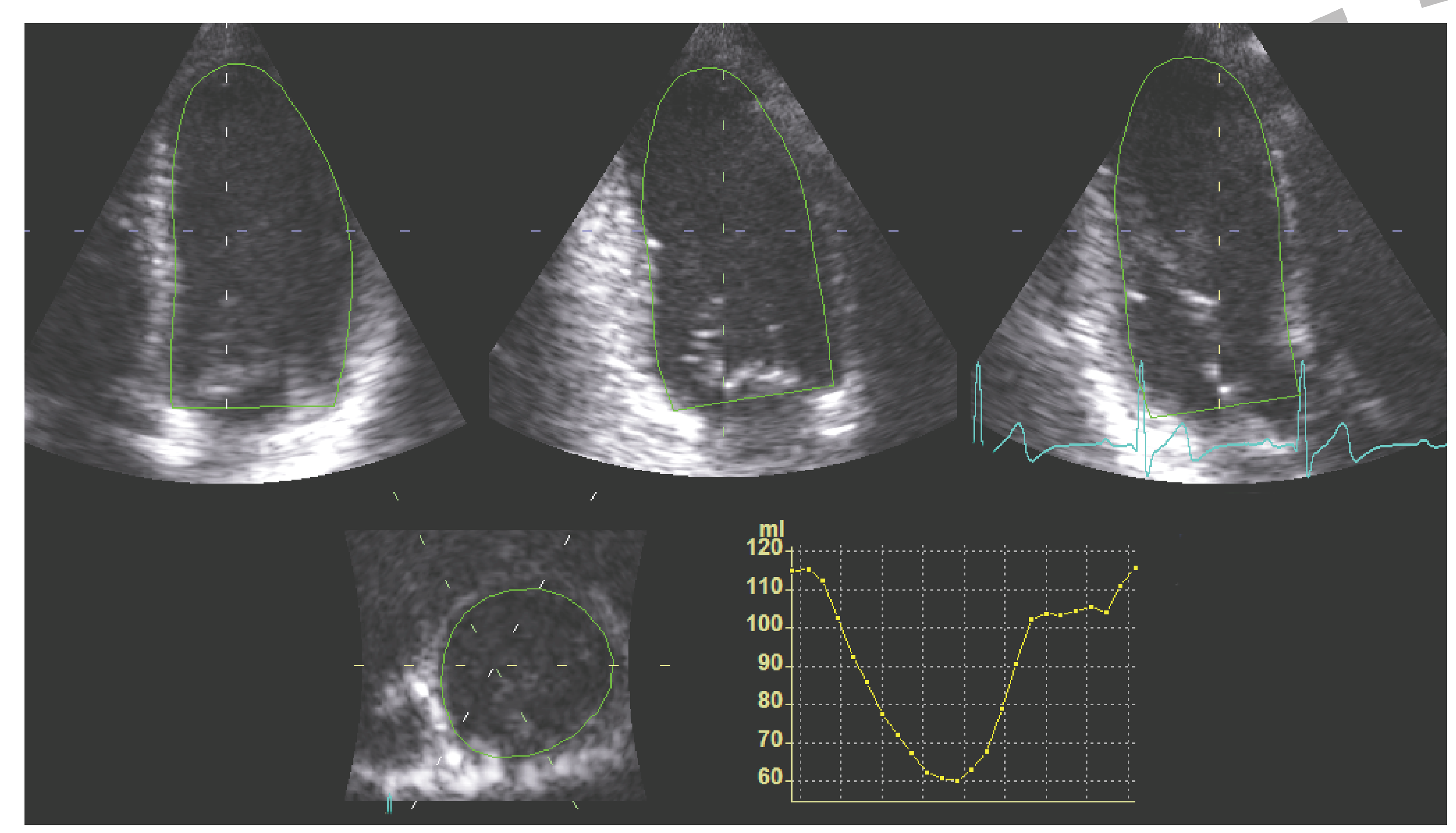
- Edge-detection performed radially, in search normals distributed evenly over the surface.
- ~450 search normals, each consisting of 30 samples spaced 1 mm apart.
- Used a "transition criteria" as edge detector, which detects the position of the strongest edge along each search normal.



Visualization of edge-detection results in three slices through the volume

Example

- Fully automatic tracking, without user intervention.
- Robust tracking, with long radius of convergence.
- Operates in real-time, using 13% CPU power on a 2.16GHz Intel Core 2 duo.

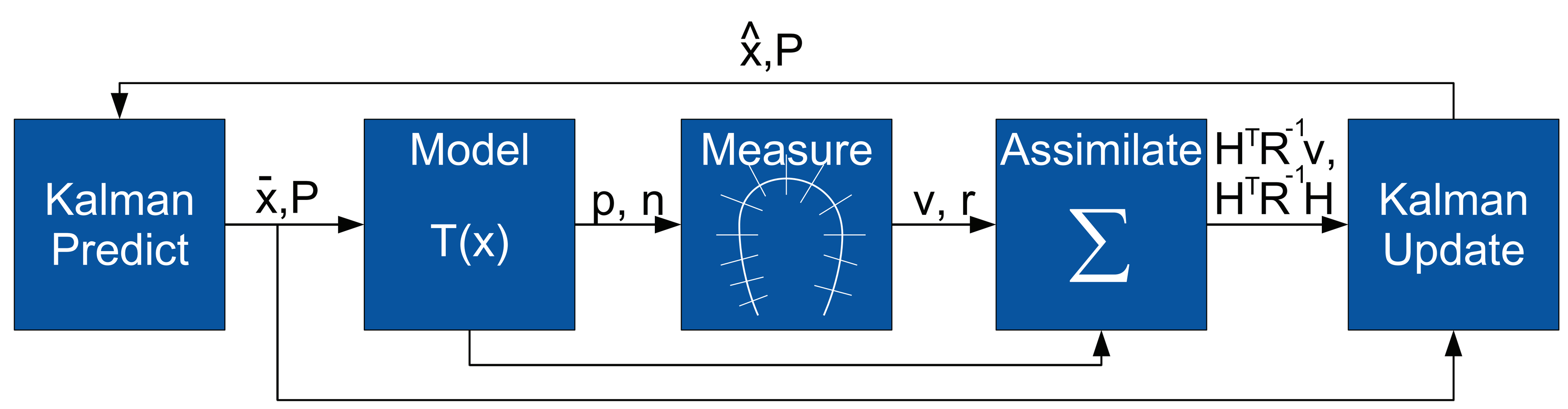


Screenshot from real-time tracking implemented on a GE Vivid 7 ultrasound scanner

Tracking framework

- Treat tracking problem as a state-estimation problem.
- **Goal:** Estimate state vector consisting of control point positions ($\mathbf{x}_l$) and global pose parameters ($\mathbf{x}_g$):

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

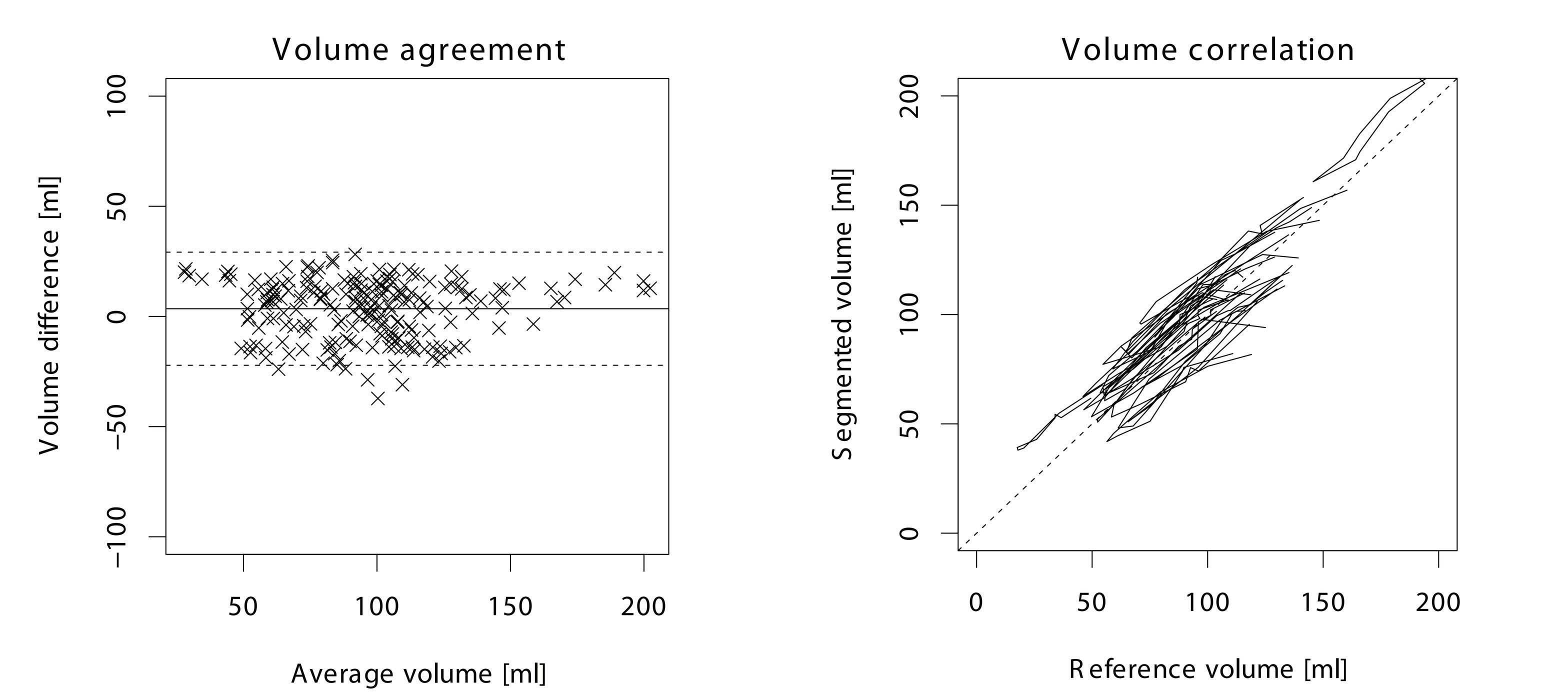


Block diagram over the separate stages in the tracking framework

- The state vector is estimated using an extended Kalman filter in a 5-step process:
  1) Use a 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 deformable model based on the prediction, and extract surface points from this model.
  3) Perform edge-detection along surface normals of the predicted model.
  - Compute normal displacement (v), measurement variance (r) and a measurement vector (**h**) for each edge i:
  $$v_i = \mathbf{n}_i^T(\mathbf{p}_{obs,i} - \mathbf{p}_i) \qquad \mathbf{h}_i^T = \mathbf{n}_i^T \frac{\partial \mathbf{T}(\mathbf{p}_0, \mathbf{x})_i}{\partial \mathbf{x}}$$
- Measurement update:
  - Assume that the measurements are independent
  - Perform outlier removal for edge measurements.
  4) Assimilate edge-detection measurements in information space:
  $$\mathbf{H}^T\mathbf{R}^{-1}\mathbf{v} = \sum_i \mathbf{h}_i r_i^{-1} v_i$$
  $$\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H} = \sum_i \mathbf{h}_i r_i^{-1} \mathbf{h}_i^T$$
  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

- Tested in 21 unselected 3D echocardiography recordings, acquired using a GE Vivid 7 scanner.
- Meshes from the automatic real-time tracking was compared to meshes from a semi-automatic segmentation tool (GE Vingmed).
- Bland-Altman analysis of the volumes yields a 4.1 ml bias, with 95% limits of agreement in the interval 4.1±24.6 ml, and a strong correlation (r = 0.92).
- The average point to surface distance between the mesh and the reference surfaces was 2.7 mm.



Volume correspondence throughout the cardiac cycle, for all frames in all of the 21 recordings