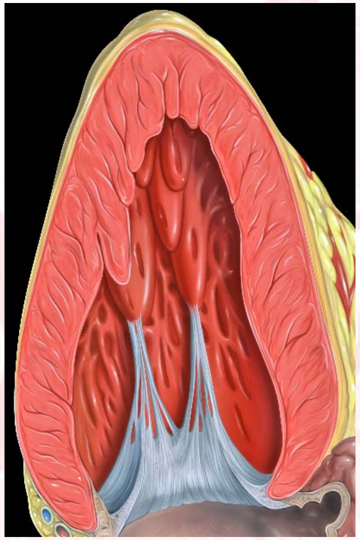
Real-time left ventricular speckle-tracking with subdivision surfaces

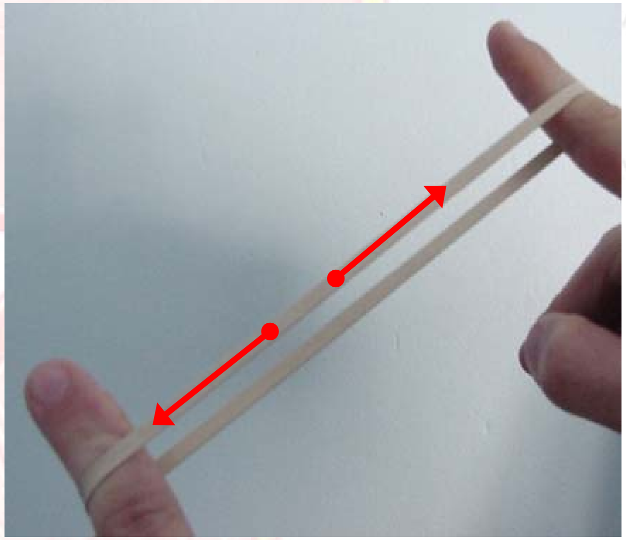
Estimation of myocardial strain in 3d echocardiography

Fredrik Orderud[1], Gabriel Kiss[1], Stian Langeland[2],
Espen W. Remme[3], Hans Torp[1], Stein I. Rabben[2]
1 Norwegian Univ. Science & Technology, Norway; 2 GE Vingmed Ultrasound, Norway; 3 Rikshospitalet, Norway

Motivation

- Want to detect myocardial infarction
  - Characterized by regions of reduced contractility
- How to detect contractibility?
  - Must track material points from frame to frame
- Why not just perform image segmentation?
  - Segmentation detects shape, but does not identify material points



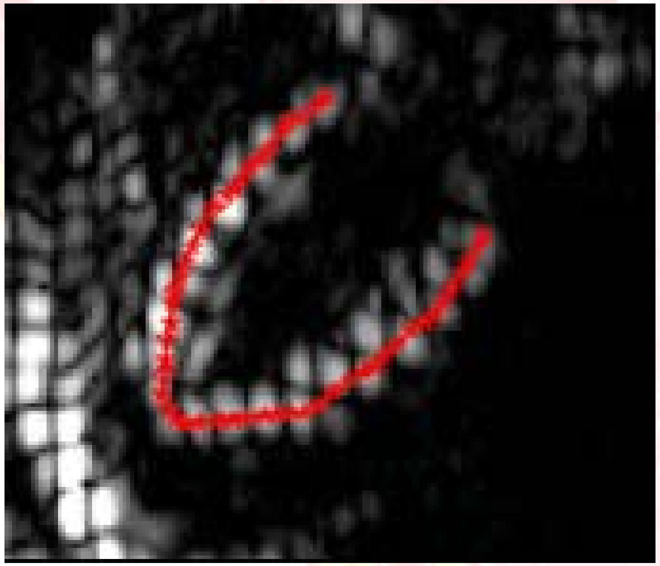


  - Stretching/contraction does not necessarily alter shape

Tracking material points

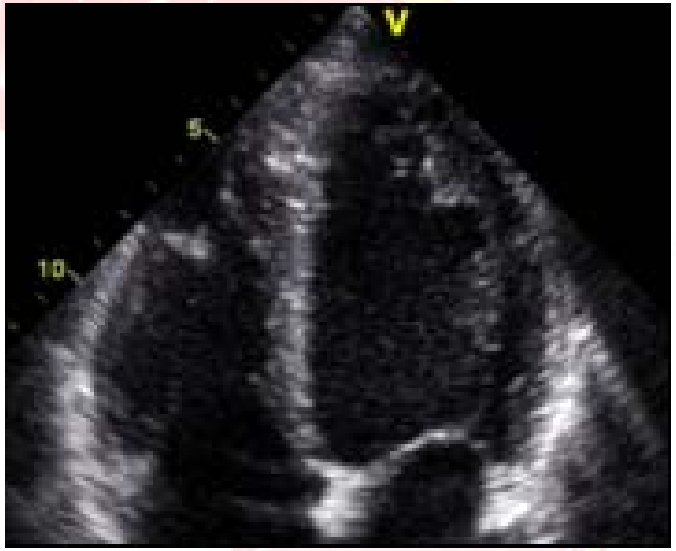
- How to track material points from frame to frame?

- In MR, “tagging” can be used to superimpose a grid over the image



  - Grid deforms with the tissue
  - Limited to 2d slices

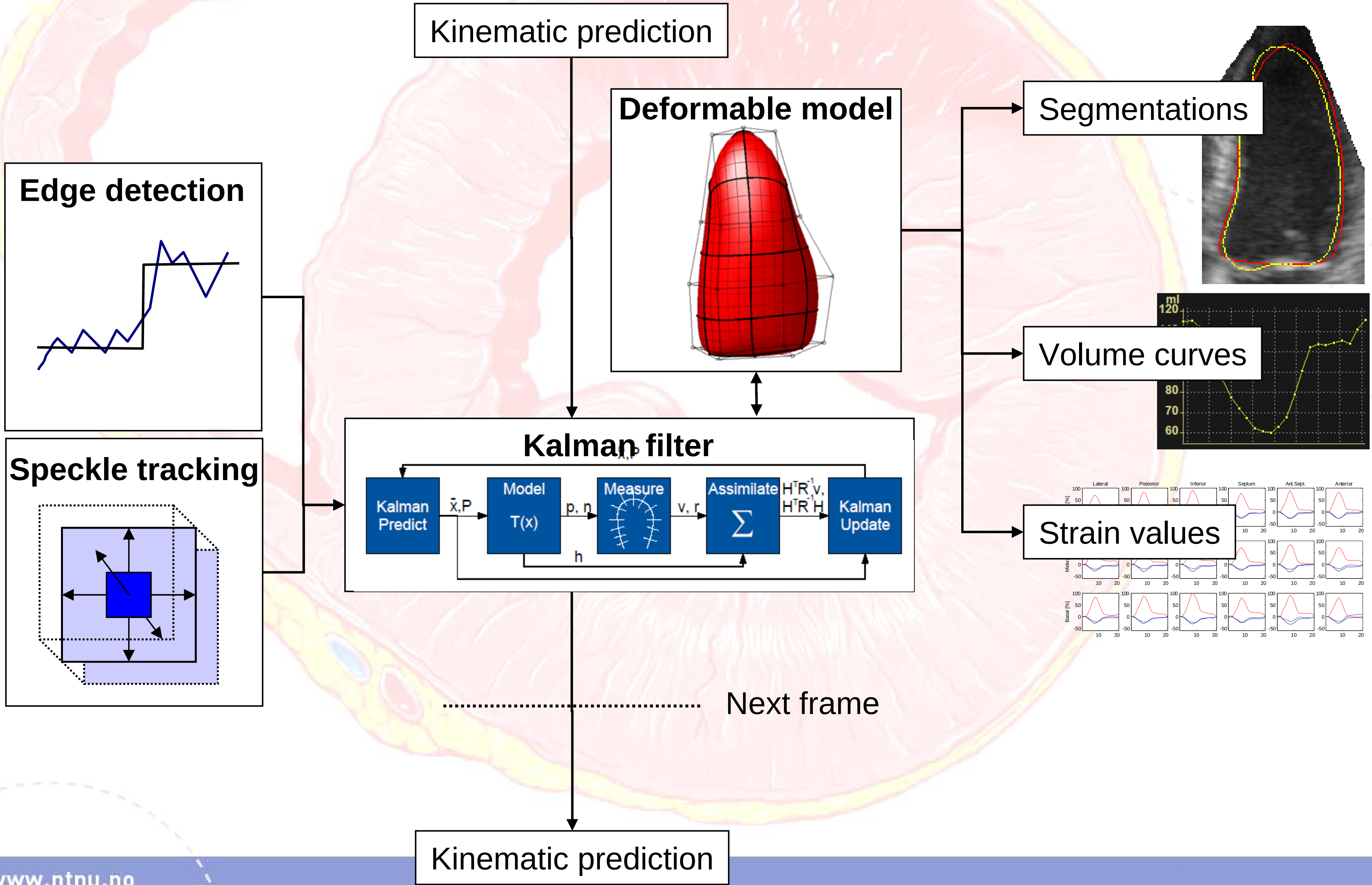
- Ultrasound images fortunately come “pre-tagged”



  - Inherent speckle-pattern also deforms with the tissue
  - “Speckle-tracking” is a clinically proven and widely used technique for cardiac strain assessment in 2d echocardiography
  - We believe that speckle-tracking also can be extended to 3d
  - There are recent publications on application of elastic registration for strain assessment in 3d ultrasound[1,2,3]

[1,2,3] A. Elen: SIPE Med.Img’07, IEEE Ultr.Symp’07, IEEE TMI (in press)

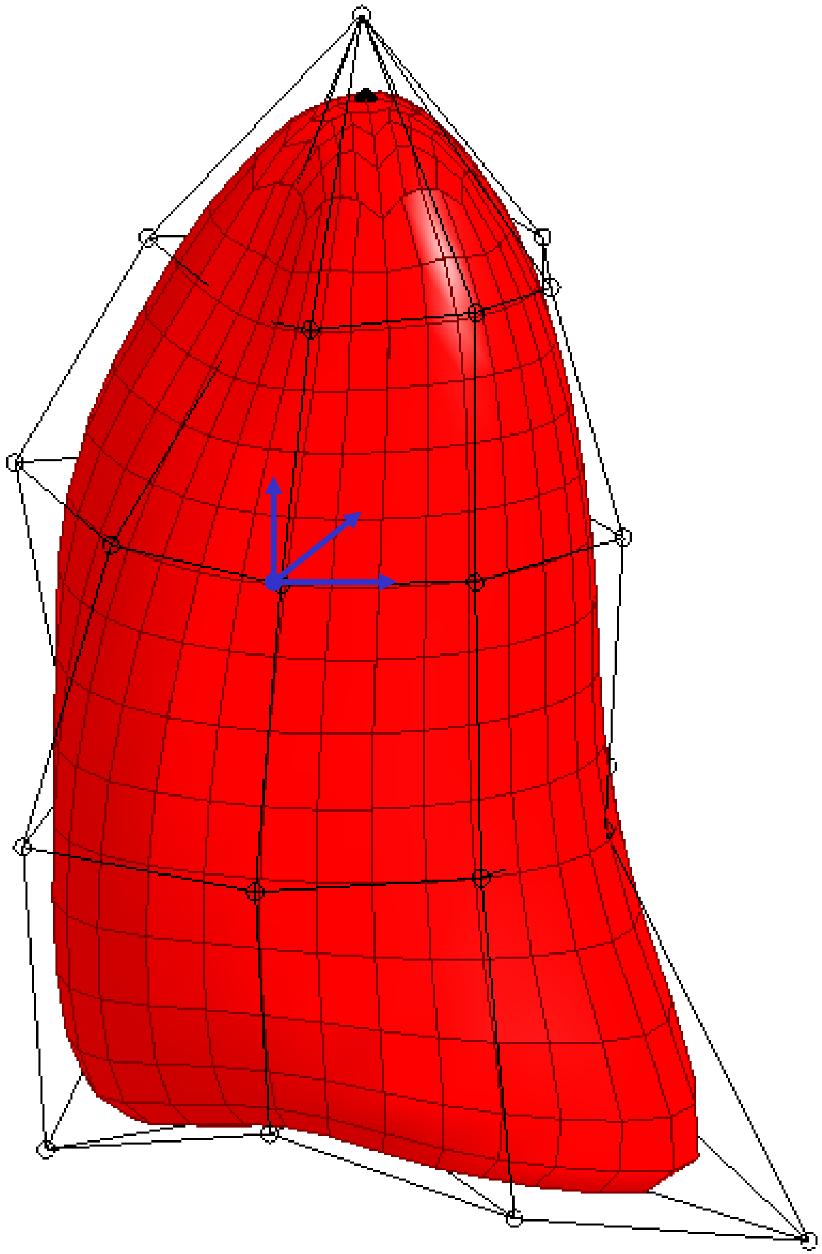
Tracking framework



Deformable model

- Use a Doo-Sabin **subdivision surface** to represent the left ventricle
  - Extension of bi-quadric B-spline surfaces to arbitrary topology.
  - Smooth surface description, that can be fitted to the cardiac wall
  - Parameterized by a mesh of control vertices
  - Defined as a recursive procedure that converge to a limit surface
  - Can also be evaluated directly without recursion[1], which is what we have done.
- State representation
  - State "x" is concatenation of x,y,z coordinate offsets for the control vertices

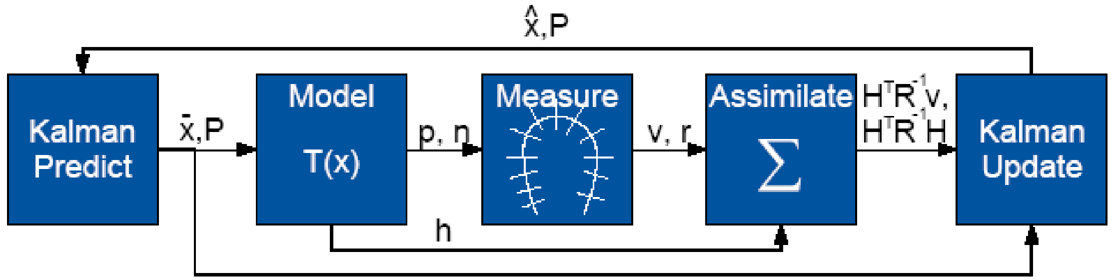
    + global trans, rot & scale.



[1] J. Stam: *Exact Evaluation of Catmull-Clark Subdivision Surfaces at Arbitrary Parameter Values*, SIGGRAPH'98

Kalman filter approach

- Predict
  - Kinematic model for temporal regularization
- Model
  - Deformable surface model for the left ventricle
- Measure
  - Edge-detection to initialize the model to the cardiac wall,
  - … or speckle-tracking to track material points.
- Assimilate
  - Perform outlier rejection.
  - Assimilate measurement results
- Update
  - Compute updated state estimate, based on prediction and measurements.
  - Create updated surface model based on state vector.



- Use a Kalman filter to fit the model to the measurements
  - Multivariate normal distribution representation (state vector + cov. matrix).
  - Balances uncertainty between temporal predictions and edge/tracking measurements.
  - Yields Bayesian least-squares estimate.

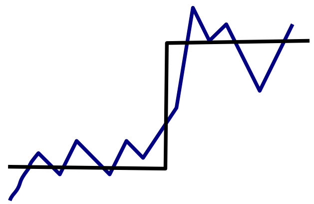
Regularized least squares fitting instead of iterative refinement!

Tracking Framework Advantages

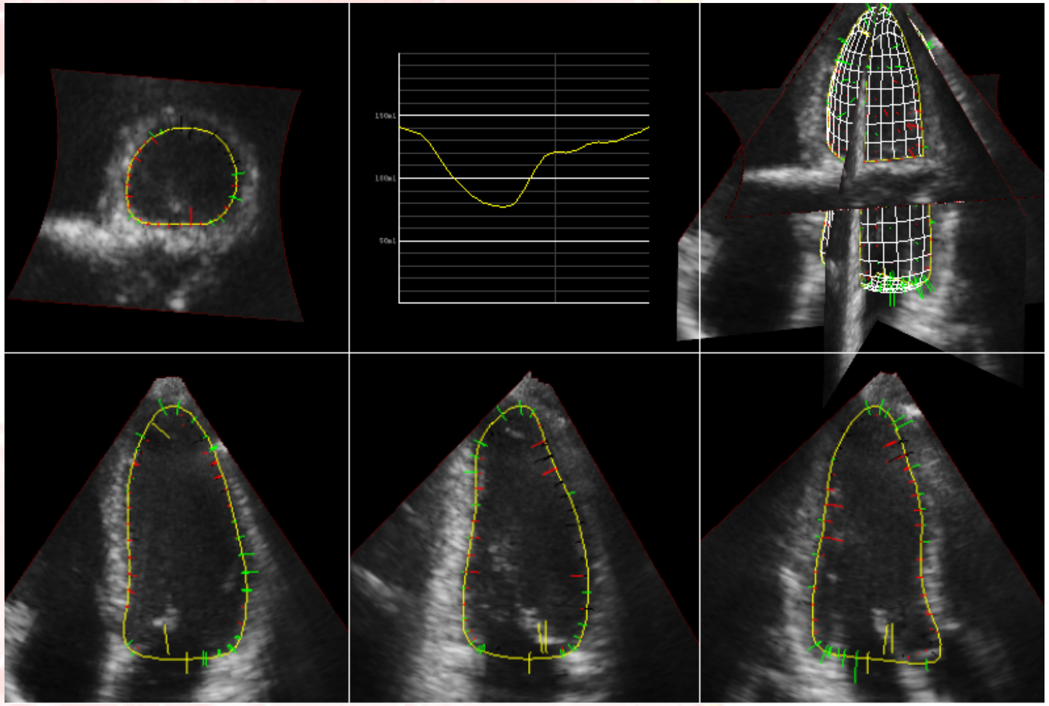
- Flexible
  - Supports a wide range of parametric models (spline- and subdivision- surfaces, polygonal-meshes, statistical shape models).
  - Models are combined with global transforms for positioning and orientation.
- Robust
  - Robust behavior, with long range of convergence.
  - Enables fully automatic initialization.
- Efficient
  - 4ms/frame for segmentation using edge-detection.
  - 40ms/frame when using speckle-tracking.
- Clinical value
  - Proven good agreement for segmented volumes to alternative segmentation tool in a limited dataset (N=21)[1,2].
  - Automatic behavior ensures excellent reproducibility.
  - We are in the process of comparing segmented volumes to commercially available volume tools (GE Auto4dQ, TomTec LV) in a bigger dataset.

[1] F. Orderud, SI. Rabben: *Real-time 3D Segmentation of the Left Ventricle Using Deformable Subdivision Surfaces*, CVPR’08.
[2] F. Orderud, J. Hansegård, SI. Rabben: *Real-time Tracking of the Left Ventricle in 3D Echocardiography Using a State Estimation Approach*, MICCAI’07.

Edge detection

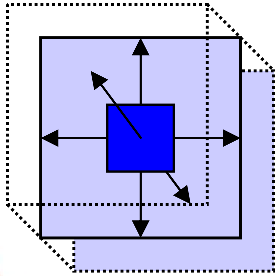


- Extract search “profiles” perpendicular to the model’ surface
- Search for edges in these profiles
  - “Transition criterion”, where the edge forms a transition from one intensity level to another
  - Determine the edge position that minimizes the sum of squared errors.
- Update model in **radial direction** based on edge-detection

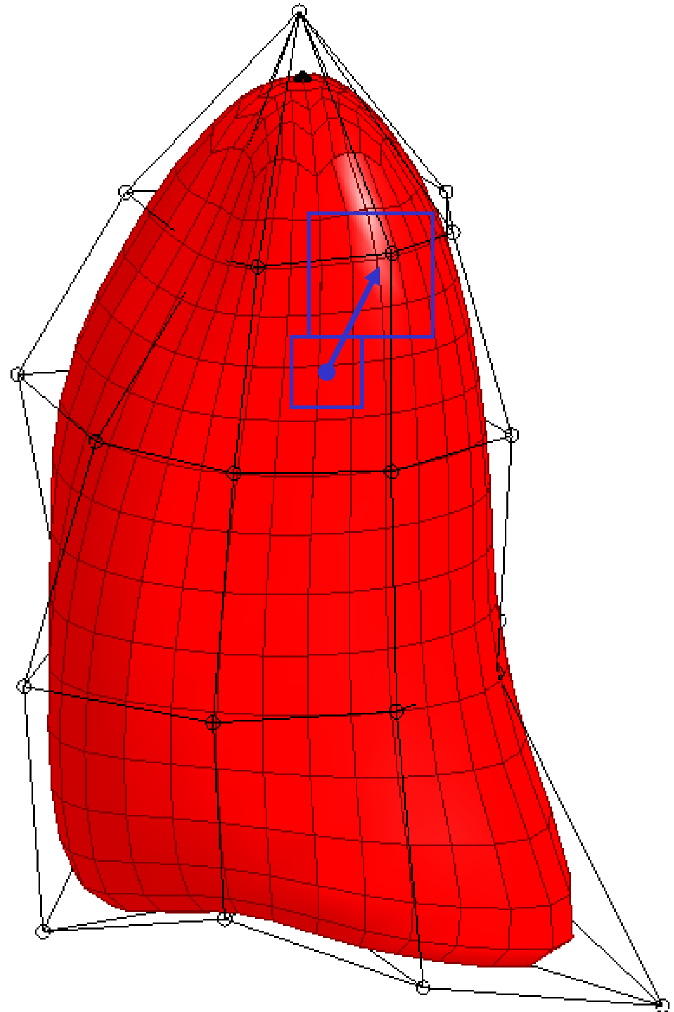


Green - edge discovered outside the surface
Red - edge detected inside the surface
Yellow - discarded outlier edge
Black - discarded too weak edge

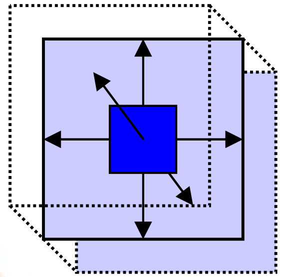
Speckle tracking (1/2)



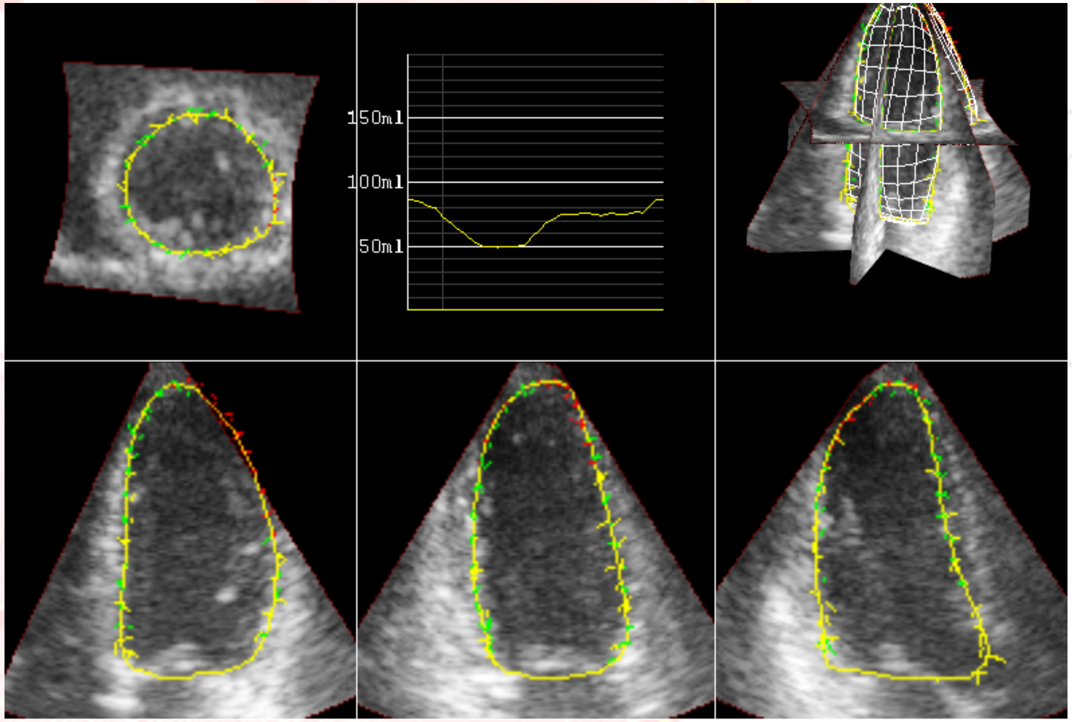
- Idea
  - Extract small “volume-patches” from the myocardium
  - Match “kernel-volumes” in one frame to “search volumes” in the next frame.
  - Update model based on the displacement vectors
- For each surface point:
  - Compute spatial position “p” and Jacobian matrix “J”.
  - Perform speckle-tracking to compute a displacement vector.
  - Discard outlier displacements.
  - Treat displacement vector as a measurement of the surface point in the Kalman filter, with Jacobian matrix as measurement matrix.



Speckle tracking (2/2)



- Implementation
  - Tracking with ~500 points, distributed evenly over the surface
  - Search for best integer displacement using sum of absolute differences (SAD) matching
  - Sub-pixel correction using Lucas-Kanade optical flow
  - Tracking directly in “raw” spherical grayscale data (not cartesian)
  - Data is decimation in the beam-propagation direction with a factor of 4 to reduce window sizes
  - Combined multi-core parallelization with vector instructions to achieve real-time performance.



Green - displacement vectors
Red - discarded displacement vectors (weak or outside sector)
Yellow - discarded outlier displacements

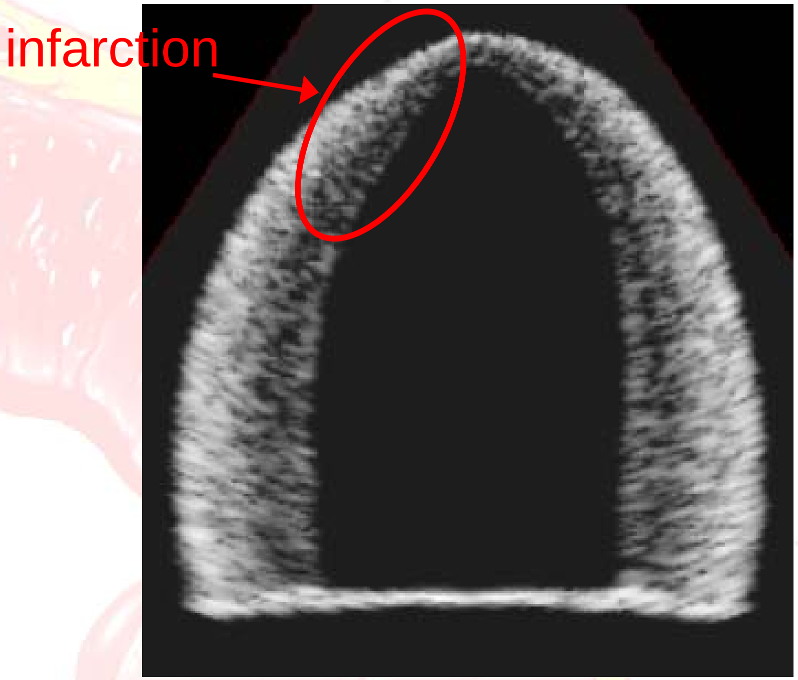
40ms/frame on a 2.2GHz Intel core 2 duo

Results

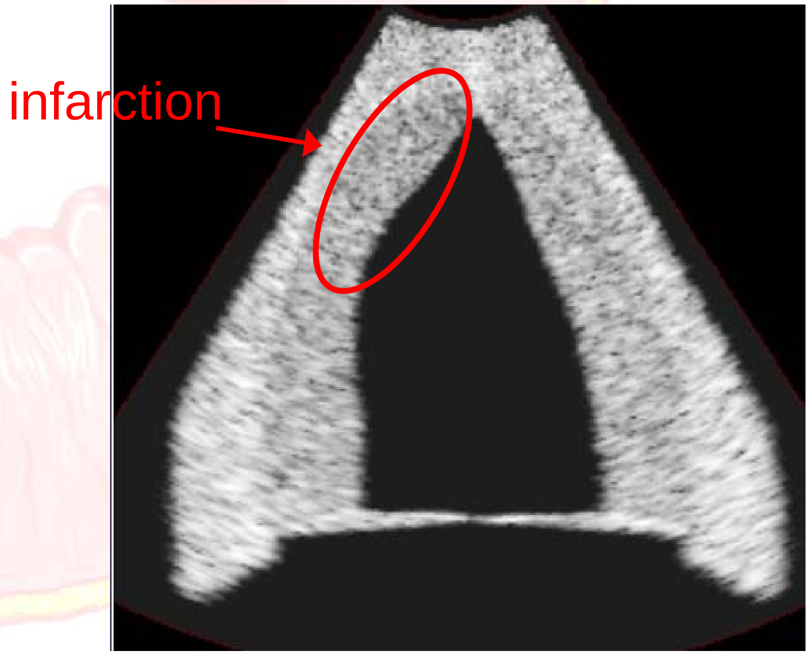
simulated & in-vivo

Simulated Data

- Based on a finite-element (FEM) simulation of a left ventricle
  - With an anterio-apical infarction
  - Motion and deformation based on internal systolic contraction and external cavity pressure.
- “K-space” ultrasound simulator
  - Configured based on acquisition settings on the GE Vivid 7 ultrasound scanner
  - Initialized with scatter points from the FEM model
- Two simulations were generated
  - One with an ellipsoid shape for the LV
  - One with a shape based on a “canine” heart

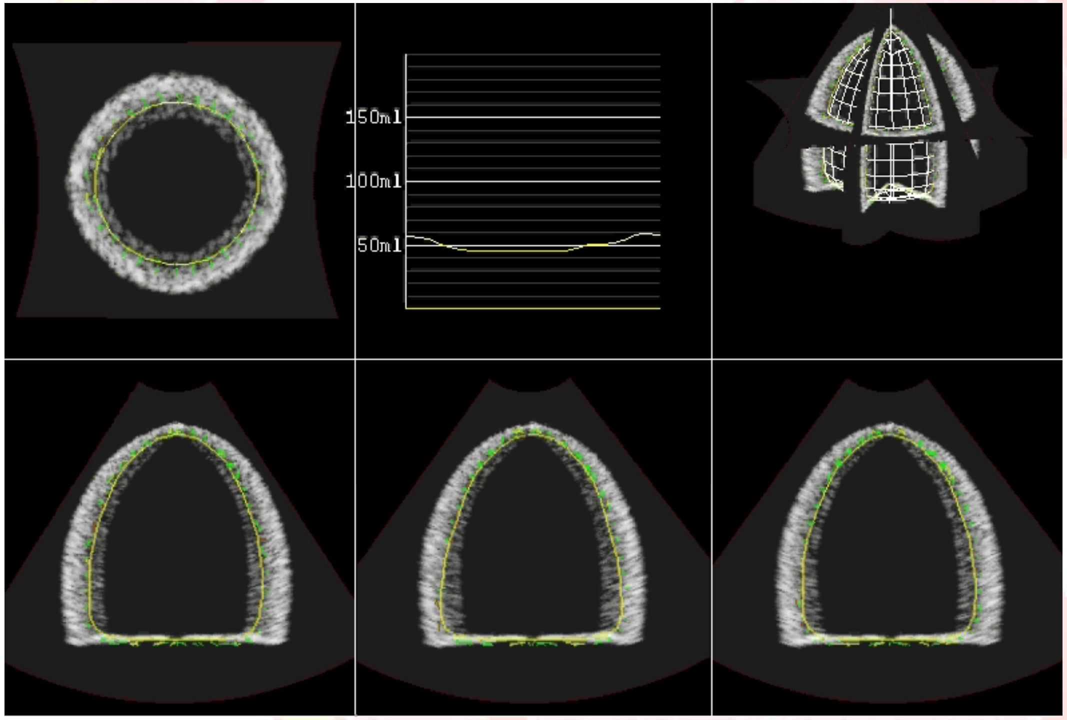


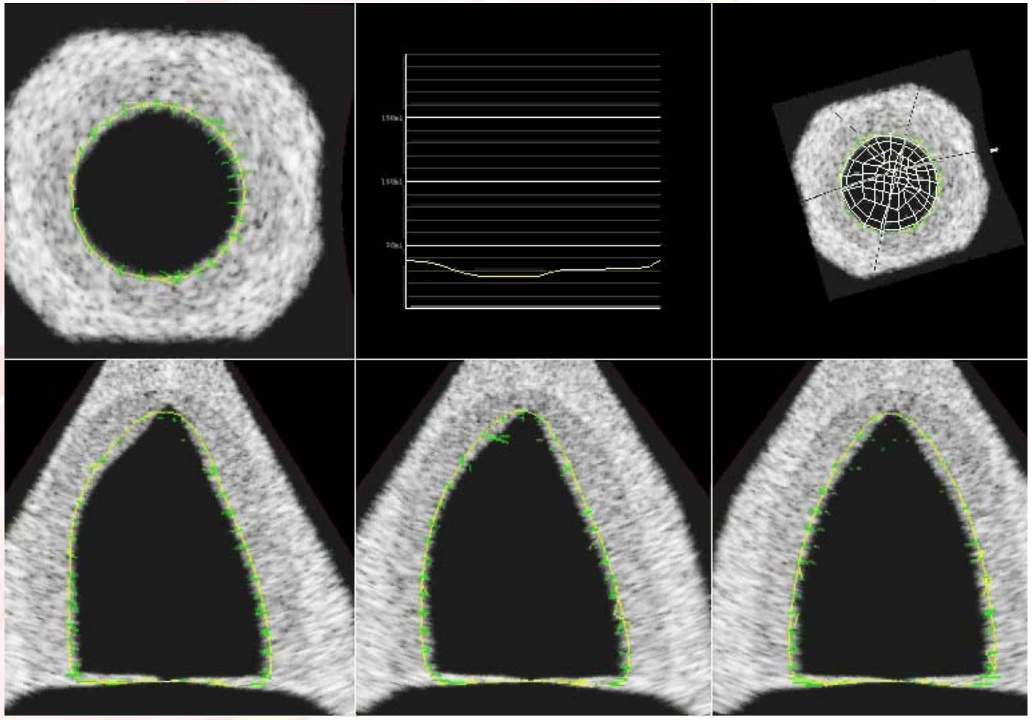
Ellipsoid simulation



Dog-heart simulation

Simulated results





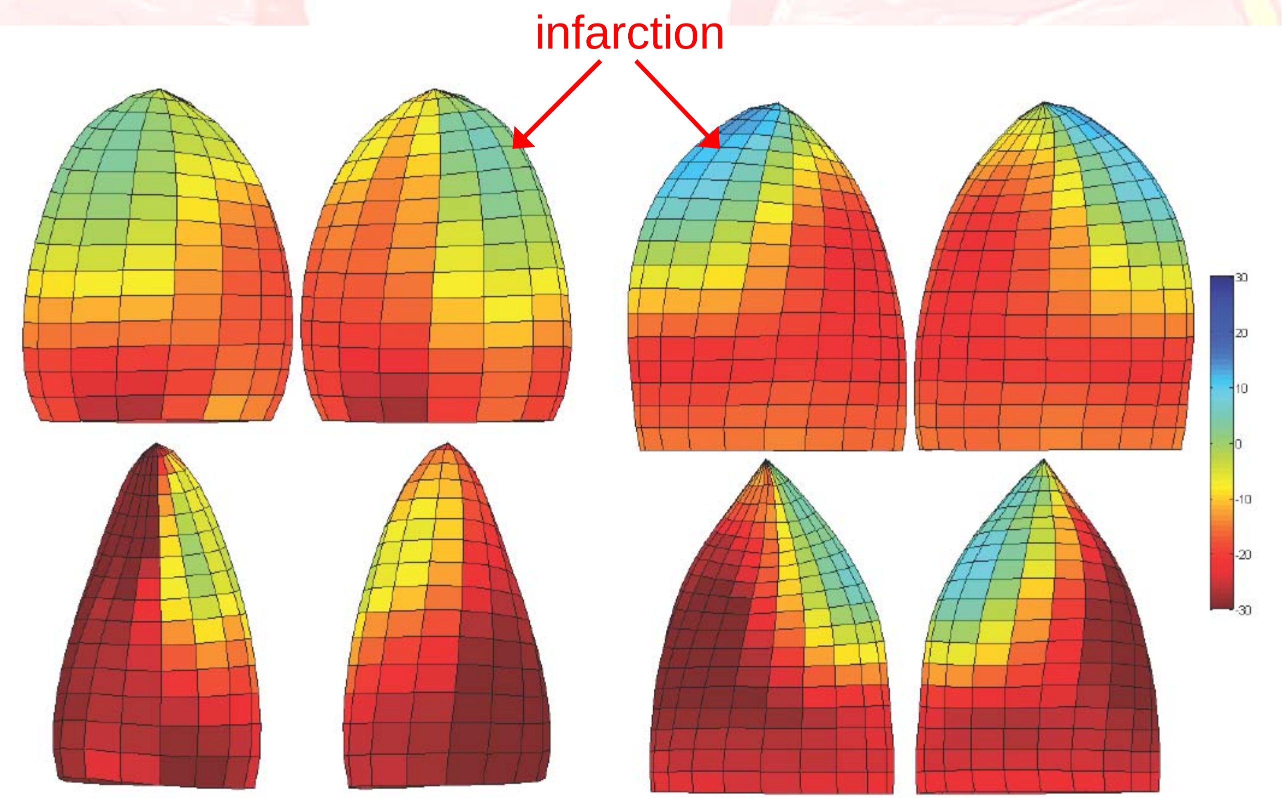
Simulated results

- Visualization of strain at end-systole (ES) – maximum contraction:

- Able to correctly identify infarcted region in simulations
- Absolute strain values are underestimated

Simulation A:

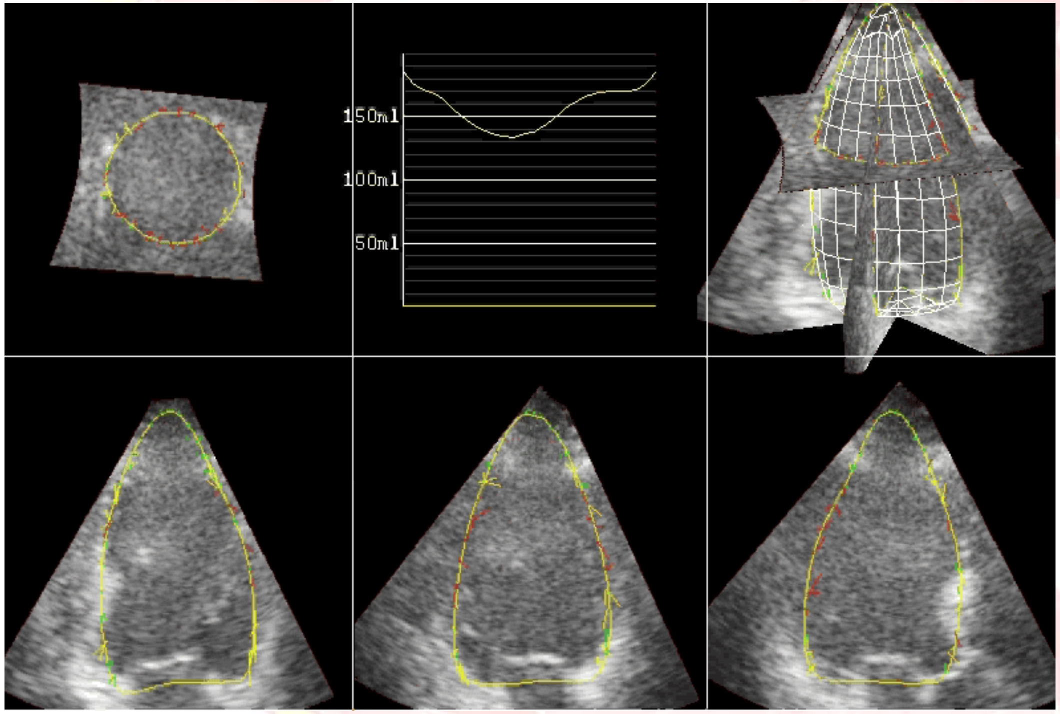
Simulation B:

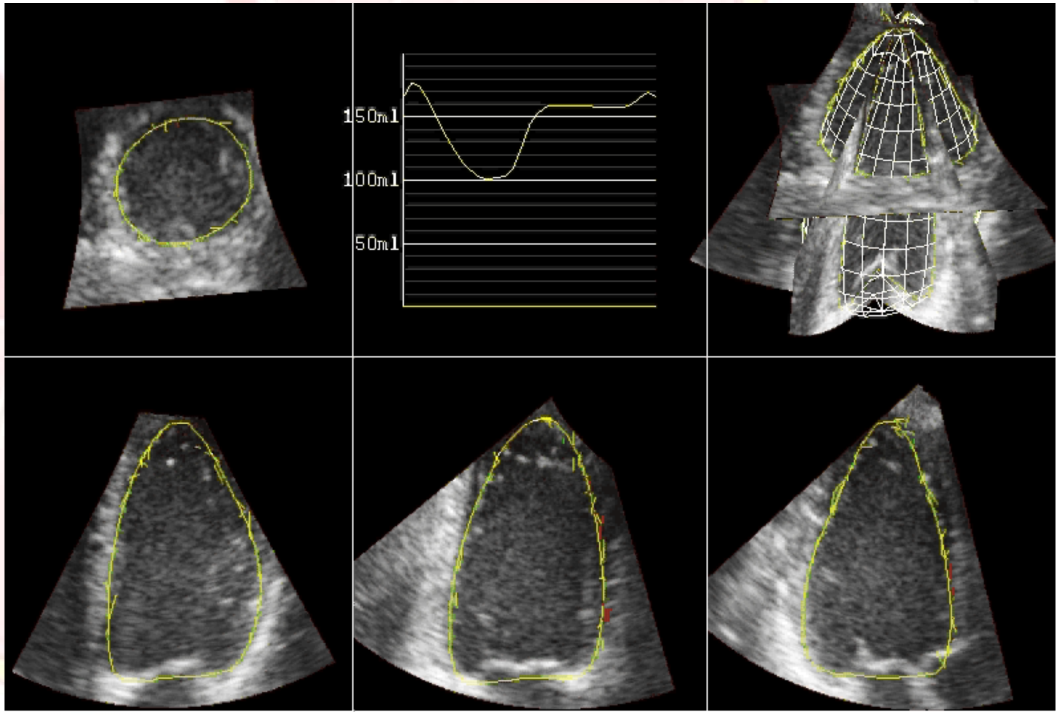


Estimated

Ground truth

In-vivo results





In-vivo results

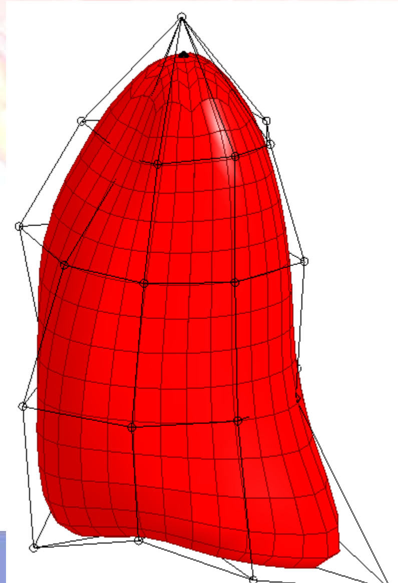
- Tested in 21 unselected in-vivo recordings
  - 50% with cardiac disease
  - No ground truth available
- Evaluated tracking drift for the model, after tracking in an entire cycle
  - Block-matching between successive frames drifts over time, due to cumulative error build-up
  - Good tracking should exhibit low drift values
- More challenging than simulations, because
  - Image artifacts, such as drop-out and reverberation
  - Poor image quality in the near-field
  - Especially important to have a model to “fill in the blanks”

	Absolute drift	Relative drift
Simulation drift	0.58 +/- 0.70mm	8.58 +/- 10.59%
In-vivo drift	2.7 +/- 1.0mm	12.08 +/- 2.09%

95% conf. intervals (mean +/- 1.96std)

Discussion

- Trade-off between accuracy and resolution
  - Displacement vectors from speckle-tracking are very noisy
  - Subdivision surface provides inherent smoothing to the deformation field
  - Model resolution can be adjusted to balance the spatial smearing against locality of the deformation field



- In-vivo challenges:
  - Speckle pattern decorrelates rapidly
  - Current 3d echo recordings have lower temporal and spatial resolution than 2d recordings, which makes tracking difficult
  - Future scanners are believed to improve the situation due to more parallel beam-forming
  - 3d tracking does, however, avoid decorrelation due to out-of-plane motion
- Experienced problems:
  - Problems tracking circumferential rotation of the apex in-vivo due to near-field noise

Conclusions

- The Kalman-tracking framework can be extended with 3d speckle-tracking
  - Enables tracking material deformation in addition to shape
  - Edge-detection to initialize the model
  - Speckle-tracking to track material deformations
- It is computationally feasible to perform the tracking in real-time
  - Can potentially enable instant and automatic infarction detection

- Future work
  - Tracking not mature enough yet to have clinical value for in-vivo data.
  - More work required to improve & tune the algorithms
  - Bidirectional tracking can be used to eliminate drift due to cumulative buildup of errors
  - In-vivo results should be compared to 2d echo or late-enhancement MRI
- Quantitative analysis
  - More quantitative results on the simulations will be presented on the IEEE Ultrasonics symposium in Beijing in November

Thank you