

Ultrasound Guided Procedures

September 18, 2011

MICCAI 2011 Tutorial on Image-Guided Interventions

Wolfgang Wein

Agenda

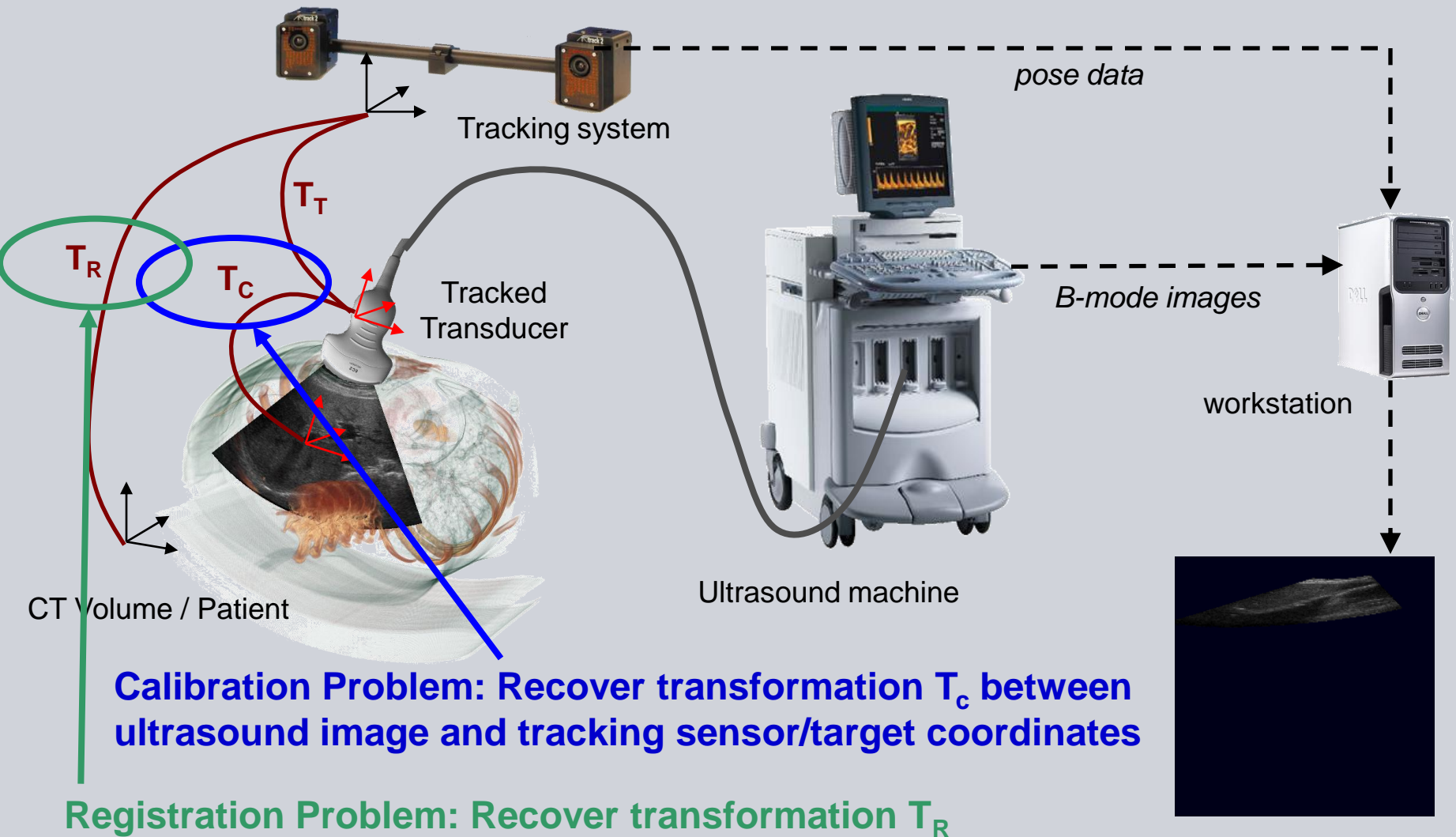
- Challenges of 3D Freehand Ultrasound
- Image-based CT-Ultrasound Registration
- Real-time respiratory motion compensation
- Visual Computing / GPU Algorithms
 - Visualization
 - 3D Freehand Ultrasound Reconstruction
 - Ultrasound Simulation
- Clinical Applications
 - Liver RFA
 - Prostate Biopsy
 - Cardiac EP Procedures
- Conclusion

About Myself

- Ph.D. student from 2004-2006 at Computer Aided Medical Procedures (CAMP), Prof. Nassir Navab, Technische Universität München (TUM)
- March 2006 – April 2010: Research Scientist at Siemens Corporate Research (SCR), Princeton, NJ USA
- Since May 2010: CTO at White Lion Technologies AG, München, Germany

→ The work presented in the following was done at CAMP and SCR

3D Freehand Ultrasound

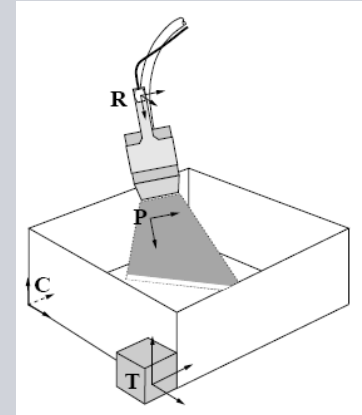


3D Freehand Ultrasound Calibration

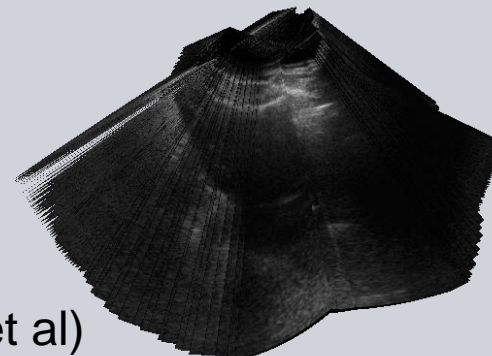
- Phantoms with geometric features:
 - Plane (Single-Wall calibration, Prager et al)
 - Spheres / Lines (Cross-Wire, N-Wire, Trobaugh et al, Prager et al)
 - Wedges (Boctor et al)
- Other Phantoms:
 - MI-based calibration of Agar phantom (Blackall et al)
- Phantom-less:
 - Tracked tool submerged in water (Muratore et al, Khamene et al)
- Image-based in-vivo:
 - Monitoring of calibration (Boctor et al)
 - Alignment of interleaved slices (Wein et al)



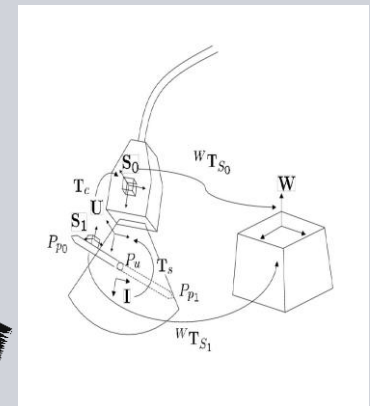
Agar Phantom (Blackall '05)



Single-Wall (Prager '97)



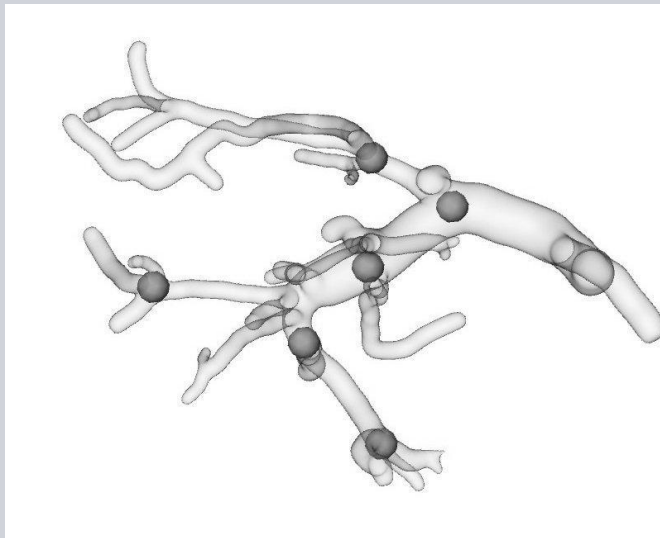
Interleaved sweep (Wein '08)



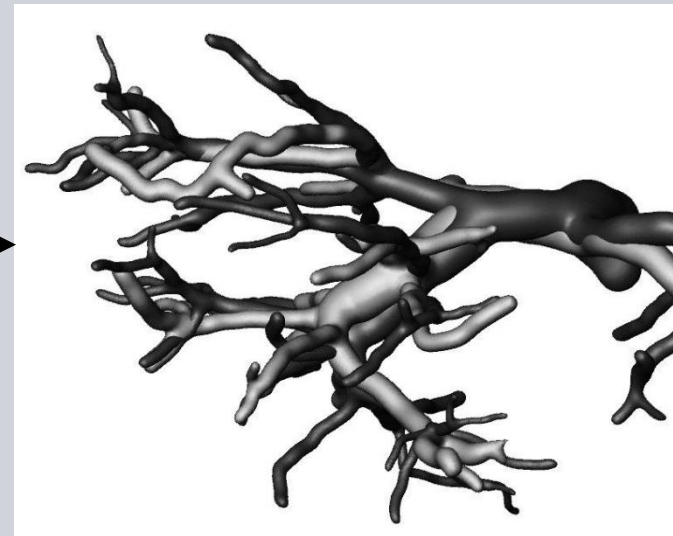
Tracked Tool (Khamene '05)

CT-Ultrasound Registration - Overview

- Manual vs. automatic registration
- Feature-based vs. intensity-based registration
- B-mode US vs. secondary imaging modes



Liver vasculature derived from contrast-CT and doppler ultrasound; defined landmarks



**After registration
(courtesy of Papenberg et al., SPIE MI 2008)**

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Automatic CT-US Registration – General Approach



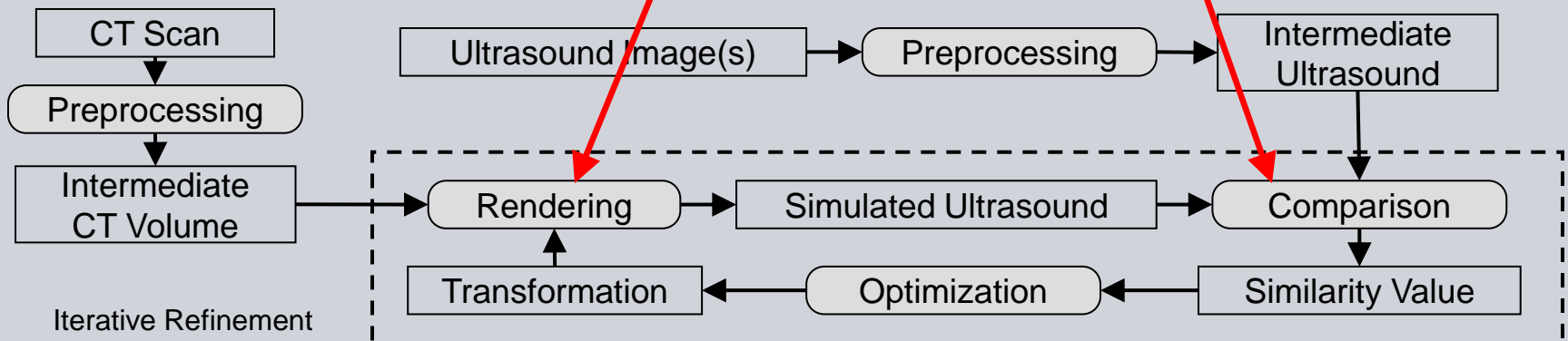
CT



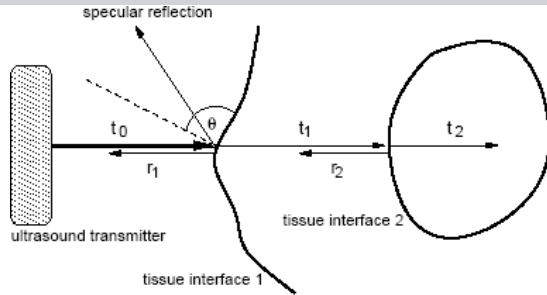
US

- Image-based registration difficult:
- Two physically very different modalities → different representation of anatomy
- Limited quality, artifacts etc.

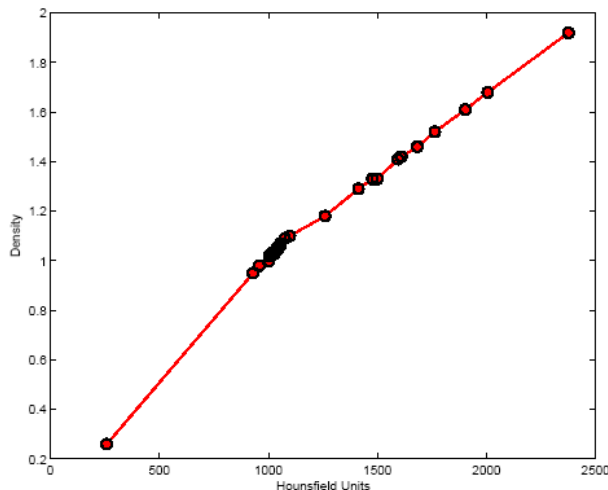
Crucial components:
 Extraction of US information from CT
 Assessing alignment



Ultrasound simulation from CT



Multiple reflection of ultrasonic waves at tissue interfaces



Density & Acoustic Impedance can be estimated roughly from CT

(1) Reflection and transmission at an interface depend on angle and acoustic impedances:

$$\Delta r(Z_1, Z_2, \theta) = (\cos \theta)^n \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

$$t(Z_1, Z_2) = 1 - \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2}$$

(2) Estimation from CT:

$$\Delta r(\vec{x}, \vec{d}) = \left(\vec{d}^T \frac{\nabla \mu(\vec{x})}{|\nabla \mu(\vec{x})|} \right)^n \left(\frac{|\nabla \mu(\vec{x})|}{2\mu(\vec{x})} \right)^2$$

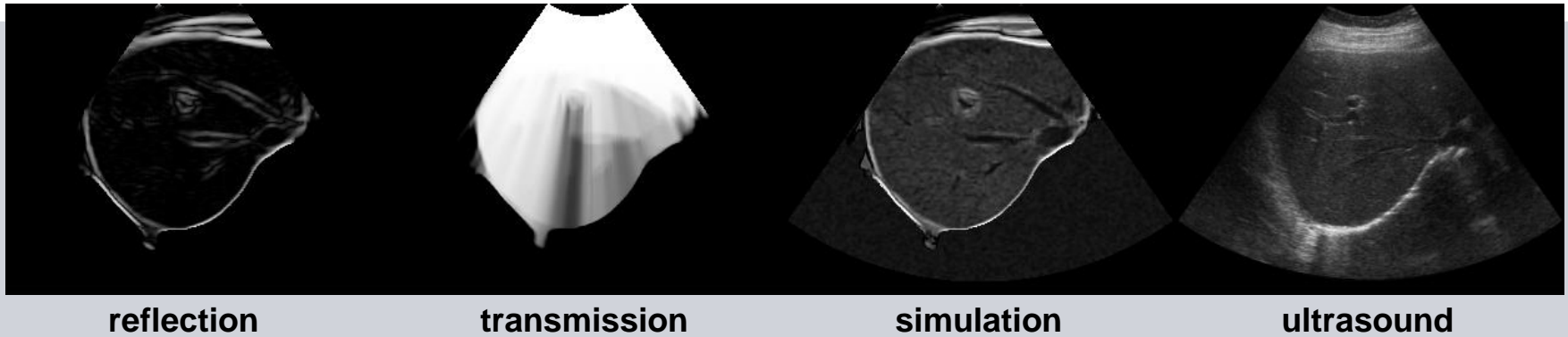
for $n = 1$: $\Delta r(\vec{x}, \vec{d}) = \left(\vec{d}^T \nabla \mu(\vec{x}) \right) \frac{|\nabla \mu(\vec{x})|}{(2\mu(\vec{x}))^2}$; $t(\vec{x}) = 1 - \left(\frac{|\nabla \mu(\vec{x})|}{2\mu(\vec{x})} \right)^2$

(3) Ray-Tracing approach: Following each ultrasound scanline, updating reflected and transmitted intensity

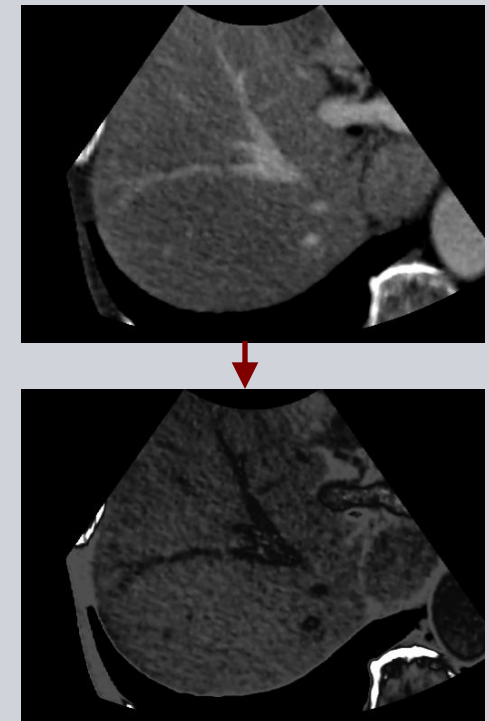
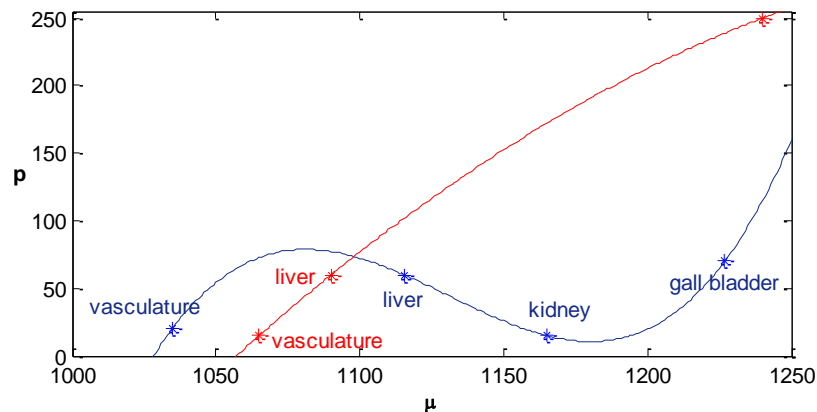
$$I(\vec{x}) = I_0 \exp \left(- \int_0^{\lambda_x} \left(\frac{|\nabla \mu(\vec{x}_0 + \lambda \vec{d})|}{2\mu(\vec{x}_0 + \lambda \vec{d})} \right)^2 d\lambda \right) \left(\vec{d}^T \nabla \mu(\vec{x}) \right) \frac{|\nabla \mu(\vec{x})|}{(2\mu(\vec{x}))^2}$$

(4) Log-compression: $r(\vec{x}) = (\log(1 + aI(\vec{x}))) (\log(1 + a))$

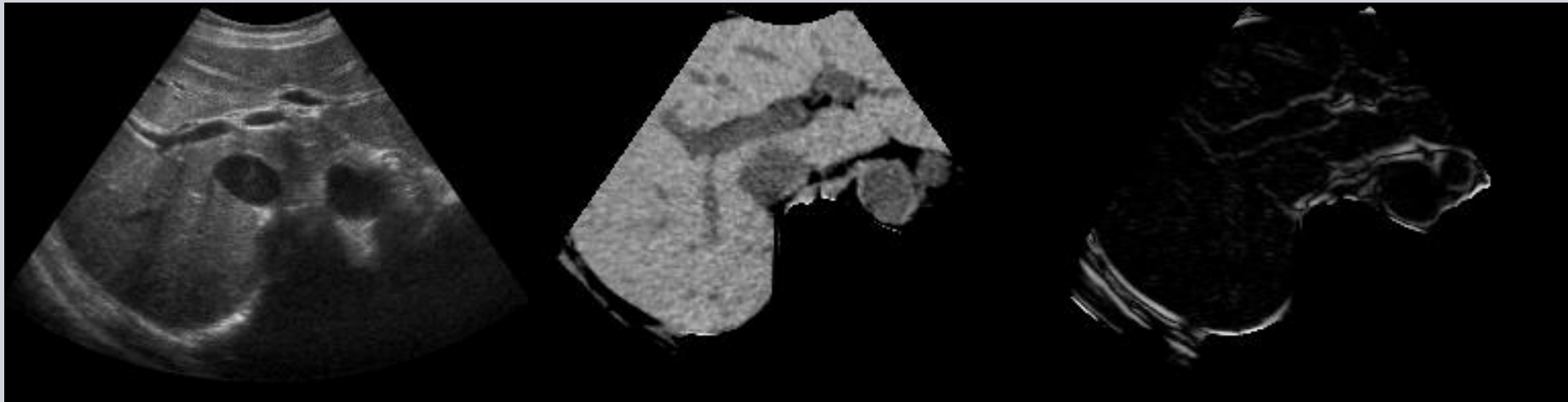
Ultrasound simulation from CT (2)



- soft tissue window from CT maps to relative echogeneity
- for CTA scans, an intensity mapping has to be applied



The LC^2 Similarity Measure



ultrasound u

echogeneity p

reflection r

We don't know the relative contribution of simulated echogeneity and reflection to the ultrasound intensity!

The LC² Similarity Measure

(1) Generalized Correlation Ratio:

$$CR = 1 - \frac{\sum_{x \in \Omega} (U(x) - f(\mu(T(x))))^2}{|\Omega| \text{Var}(U)}$$

(3) The parameters α , β and γ minimize:

$$\left\| M \begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} - \begin{pmatrix} u_1 \\ \vdots \\ u_n \end{pmatrix} \right\|^2 \quad \text{with } M = \begin{pmatrix} p_1 & r_1 & 1 \\ \vdots & \vdots & \vdots \\ p_n & r_n & 1 \end{pmatrix}$$

(2) We define the intensity mapping f as:

$$f(\vec{x}_i) = \alpha p_i + \beta r_i + \gamma$$



(4) we get

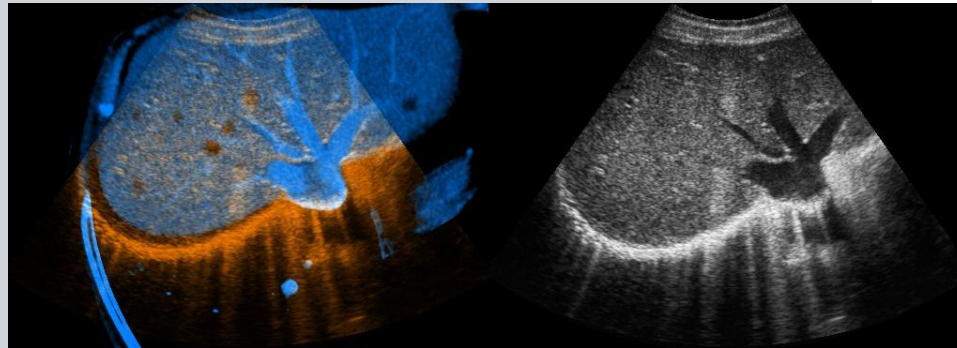
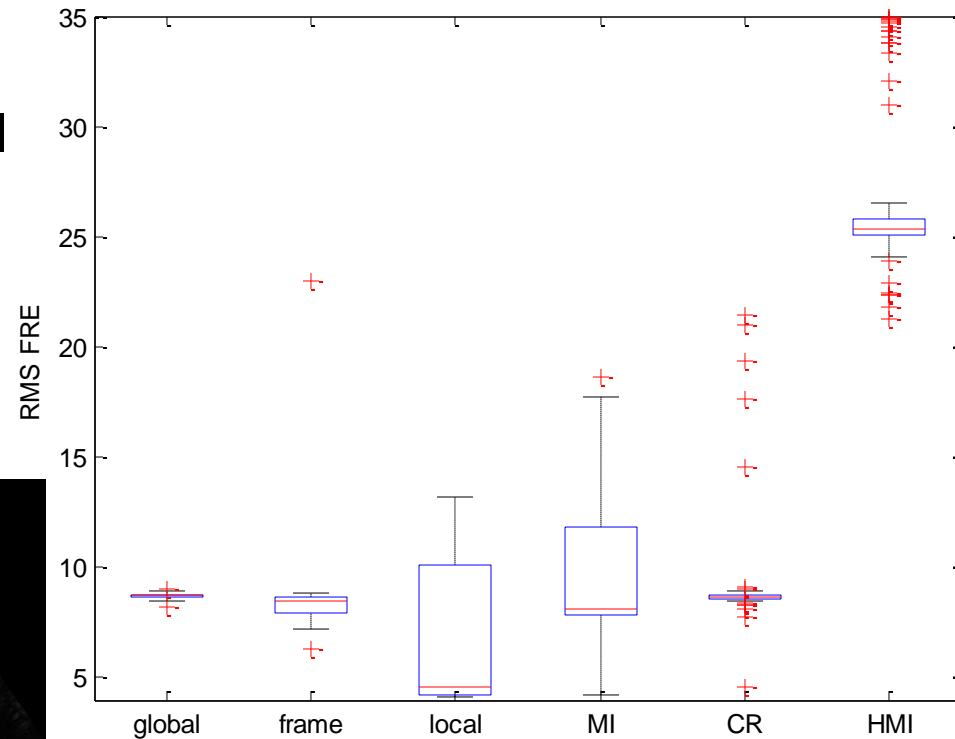
$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} = (M^T M)^{-1} M \begin{pmatrix} u_1 \\ \vdots \\ u_n \end{pmatrix} = \begin{pmatrix} \sum p_i^2 & \sum p_i r_i & \sum p_i \\ \sum p_i r_i & \sum r_i^2 & \sum r_i \\ \sum p_i & \sum r_i & n \end{pmatrix}^{-1} \begin{pmatrix} \sum p_i u_i \\ \sum r_i u_i \\ \sum u_i \end{pmatrix}$$

Linear correlation of a linear combination: LC²

- Simultaneous estimation of simulation weights and registration parameters
- Weights & similarity can be computed per sweep, per frame or locally

Comparison with standard measures

- Randomized registration study
- Global/frame/local LC² and Mutual Information, Correlation Ratio, Higher-Dimensional MI



	LC ²			statistical		
	global	frame	local	MI	CR	HMI
outliers (%)	0	1	35	29	7	100
median FRE (mm)	8.7	8.5	4.6	8.1	8.7	25.3
capture range (mm)	15.8	13.7	6.7	3.8	10.1	0

Automatic Registration Algorithm Evaluation

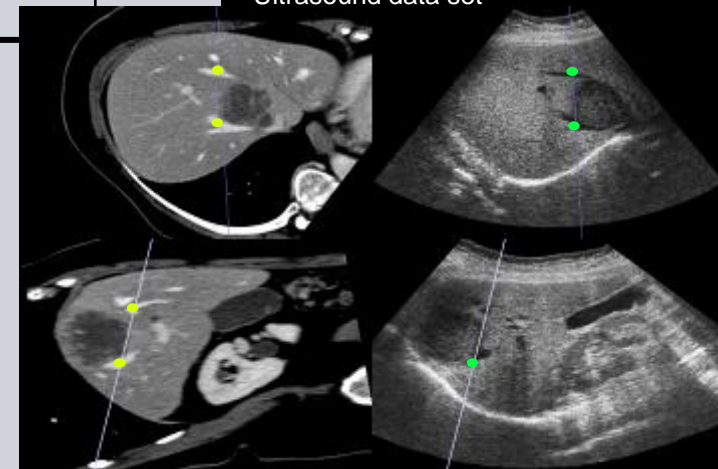
Automatic Registration statistics in 25 patients

Registration Method	Quartile 1 (mm)		Median (mm)		Quartile 3 (mm)	
	FRE	TRE	FRE	TRE	FRE	TRE
Point-based (fiducial)	3.5	4.9	4.4	7.7	5.7	12.4
Point-based (fid. + target)	4.0	3.3	4.8	4.7	7.7	7.4
Automatic Rigid Registration	6.3	5.8	10.9	8.4	12.7	11.7
Automatic Affine Registration	6.4	4.9	10.7	7.5	11.8	9.7

Automatic – 40 sec.

Manual – 10 min.

- Fiducial point in CT data set
- Corresponding fiducial point in Ultrasound data set



FRE: Fiducial Registration Error

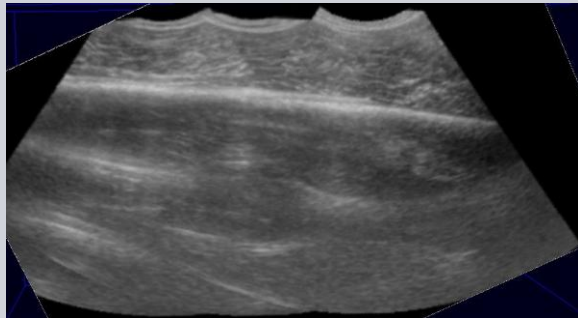
TRE: Target Registration Error

W. Wein, A. Khamene, D. Clevert, O. Kutter, and N. Navab. *Simulation and fully automatic multimodal registration of medical ultrasound*. In MICCAI 2007 conference, Brisbane, Australia, Oct. 2007.

W. Wein, S. Brunke, A. Khamene, M.R. Callstrom, N. Navab: *Automatic CT-Ultrasound Registration for Diagnostic Imaging and Image-guided Intervention*. Medical Image Analysis 12(5), pp 577-585, October 2008

3D Ultrasound Mosaicing

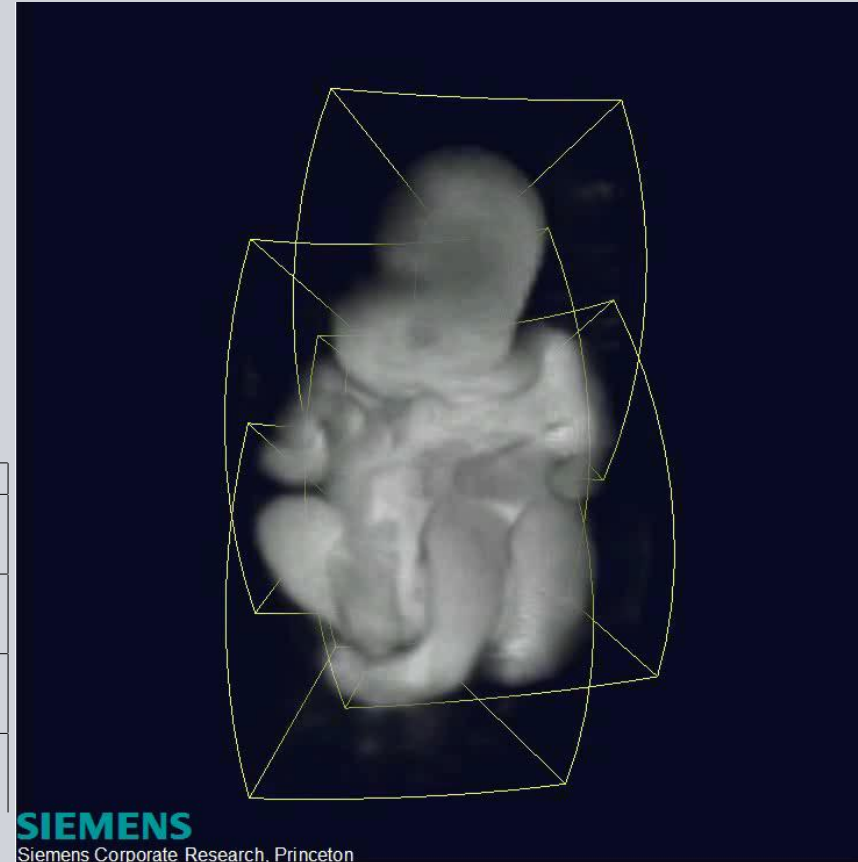
- Extending common similarity measures for multivariate registration
- Automatic registration, considering artifacts, overlap independency



MPR of stitched leg (3 volumes)



baby phantom (4 volumes)



SIEMENS
Siemens Corporate Research, Princeton

	Pairwise	Semi-Simultaneous	Full-Simultaneous	Voxel-Wise
SSD	$\mathbb{E}[(u - v^\perp)^2]$	$\sum_{i=2}^n \omega_{1,i} \mathbb{E}[(u_1 - u_i^\perp)^2]$	$\sum_{i < j} \omega_{i,j} \mathbb{E}[(u_i^\perp - u_j^\perp)^2]$	$\sum_{x_k \in \Omega} \omega_k \mathbb{E}_i[(\mu_k - u_i^\perp(x_k))^2]$
NCC	$\mathbb{E}[\tilde{u} \cdot \tilde{v}^\perp]$	$\sum_{i=2}^n \omega_{1,i} \mathbb{E}[\tilde{u}_1 \cdot \tilde{u}_i^\perp]$	$\sum_{i < j} \omega_{i,j} \mathbb{E}[\tilde{u}_i^\perp \cdot \tilde{u}_j^\perp]$	$\sum_{x_k \in \Omega} \omega_k \mathbb{E}[\tilde{u}_1^\perp \cdot \tilde{u}_2^\perp \cdots \tilde{u}_n^\perp]$
CR	$\frac{\text{Var}[\mathbb{E}(u v^\perp)]}{\text{Var}(u)}$	$\sum_{i=2}^n \omega_{1,i} \frac{\text{Var}[\mathbb{E}(u_1 u_i^\perp)]}{\text{Var}(u_1)}$	$\sum_{i < j} \omega_{i,j} \frac{\text{Var}[\mathbb{E}(u_i^\perp u_j^\perp)]}{\text{Var}(u_i^\perp)}$	-
MI	$\text{MI}(u, v^\perp)$	$\sum_{i=2}^n \omega_{1,i} \text{MI}(u_1, u_i^\perp)$	$\sum_{i < j} \omega_{i,j} \text{MI}(u_i^\perp, u_j^\perp)$	$\sum_{x_k \in \Omega} \omega_k \text{H}(P^k)$

C. Wachinger, W. Wein, and N. Navab.

Three-dimensional ultrasound mosaicing. MICCAI 2007 conference, Brisbane, Australia

Agenda

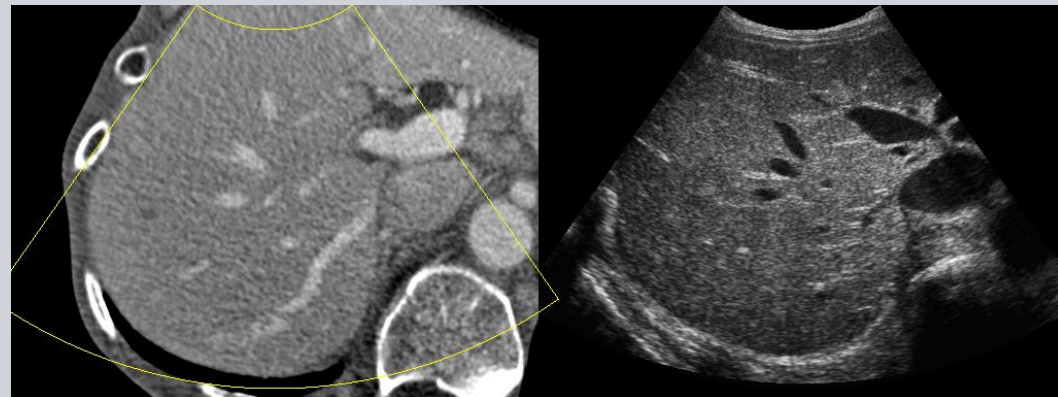
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Real-time Motion Compensation

- Dealing with moving targets for cancer treatment
- In Radiotherapy:
 - Gating techniques are established (on LINACs)
 - Adaptive RT techniques (fluoro-based) emerging (e.g. Accuray CyberKnife)
- Our goal: adaptive guidance for Interventional Oncology!
- Based on tracked 3D freehand ultrasound as real-time modality



Adjust pre-operative plan & imaging wrt. patient respiration
 → Ad-hoc, without motion model



Related Work

- Blackall et al '05: 4D MRI to 3D freehand ultrasound registration
- Khamene et al '04: 2D+t cine MRI correlated with surrogate marker
- Nakamoto et al '06: 4D motion model from laparoscopic tracked US

Problems:

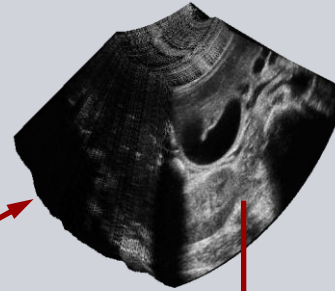
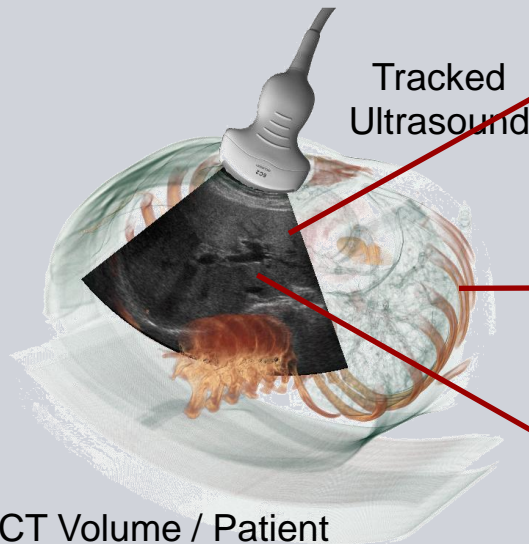
- 4D motion model needed → often not clinically feasible
- Breathing irregularities not covered

Our approach:

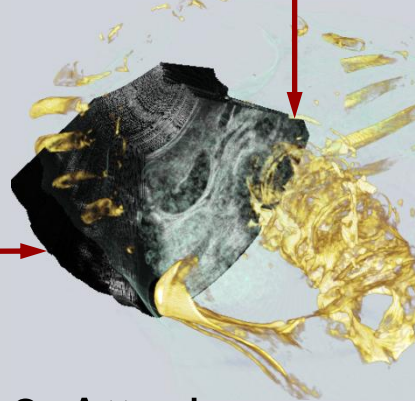
Online motion compensation without any motion model, only a surrogate sensor

Our Approach - Overview

1. Record breath-hold sweep



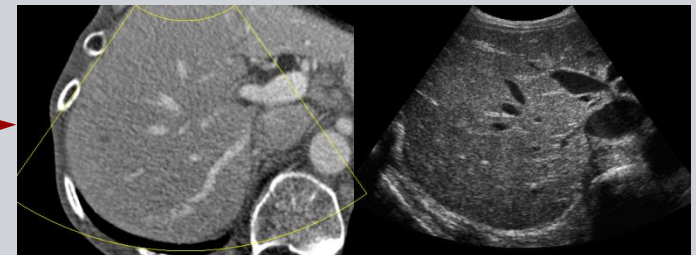
2. Register to CT
(as shown before)



3. Attach surrogate sensor, run our method



**Compensation
Algorithm**



Slice-to-Volume Registration

- Optimizing affine deformation of breath-hold volume wrt. image similarity to live US

$$\widetilde{\vec{a}}_k = \arg \max_{\vec{a}_k} \mathcal{M} \{ (I_R(\mathbf{M}_{a_k}(\vec{p})), I_{U_k}(\vec{p})), \vec{p} \in \Omega_{I_U} \}$$

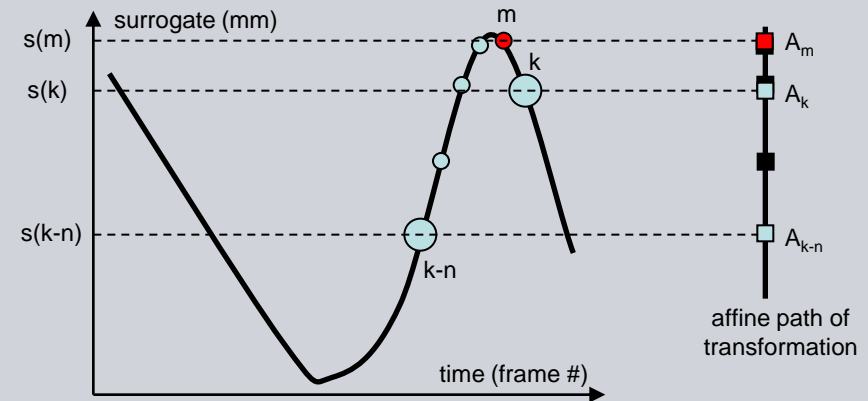
- \mathbf{M}_{a_k} is an affine transformation comprising of

$$\mathbf{M}_{a_k}(\vec{p}) = \mathbf{A}_k^{-1} \mathbf{T}_R \mathbf{T}_k \mathbf{T}_C \vec{p}; \quad \vec{p} = (x, y, 0, 1)^T$$

- We can't optimize the parameters \mathbf{A}_k of every frame
→ constraint needed!

Incorporating surrogate signal

- Assumption: Last n frames lie on a path along the transformation space
- The location along the path is derived from the surrogate signal:



$$\vec{a}_{k-n+i} = \vec{a}_{k-n} + \frac{s(k-n+i) - s(k-n)}{s(m) - s(k-n)} (\vec{a}_k - \vec{a}_{k-n}); \quad i \in [1 \dots n]$$

where

$$m = \arg \max_i |s(i) - s(k-n)|$$

Parameterization & Registration algorithm

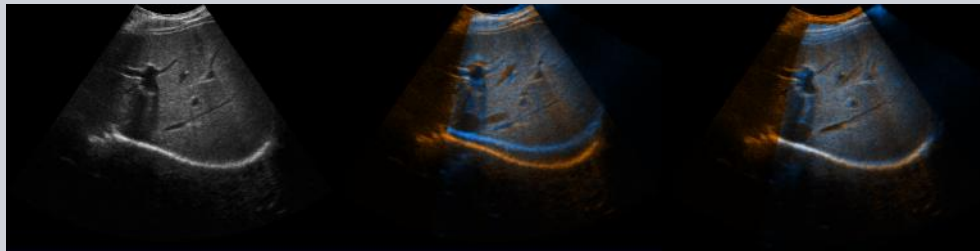
- Affine transformation has 12 DOF, however abdominal motion usually can be represented by a few modes
→ PCA-based parameter space reduction to 3 DOF
- Transformation interpolation with Lie groups:

$$\mathbf{A}_{k-n+i} = \mathbf{A}_{k-n} \exp \left(\frac{s(k-n+i) - s(k-n)}{s(m) - s(k-n)} \log(\mathbf{A}_{k-n}^{-1} \mathbf{A}_k) \right)$$

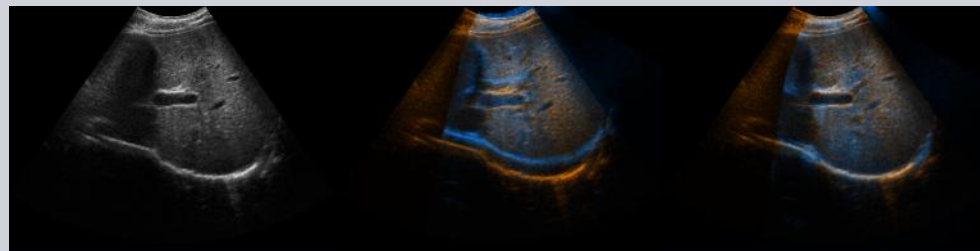
- Local Normalized Cross-Correlation (LNCC) similarity metric
- Powell-Brent optimizer on 3 PCA modes, maximum 3 sets of line minimizations

Experiments

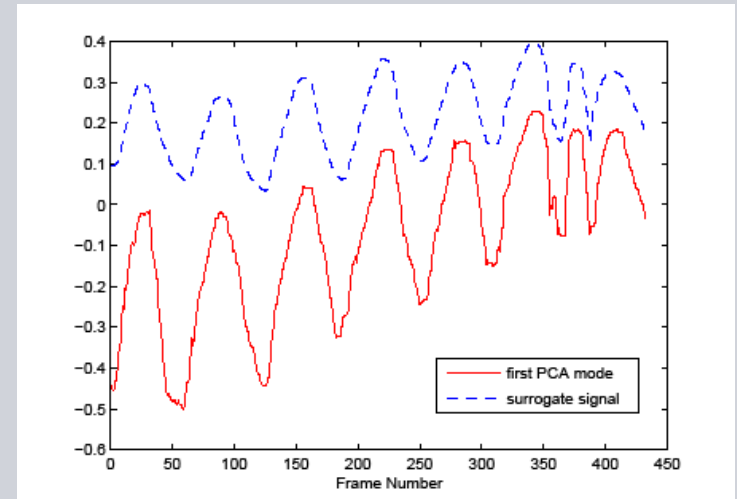
- Siemens Sequoia, abdominal 6C2 probe, magnetic tracking
- Acquisition on four volunteers (regular & irregular breathing)



mid-exhale

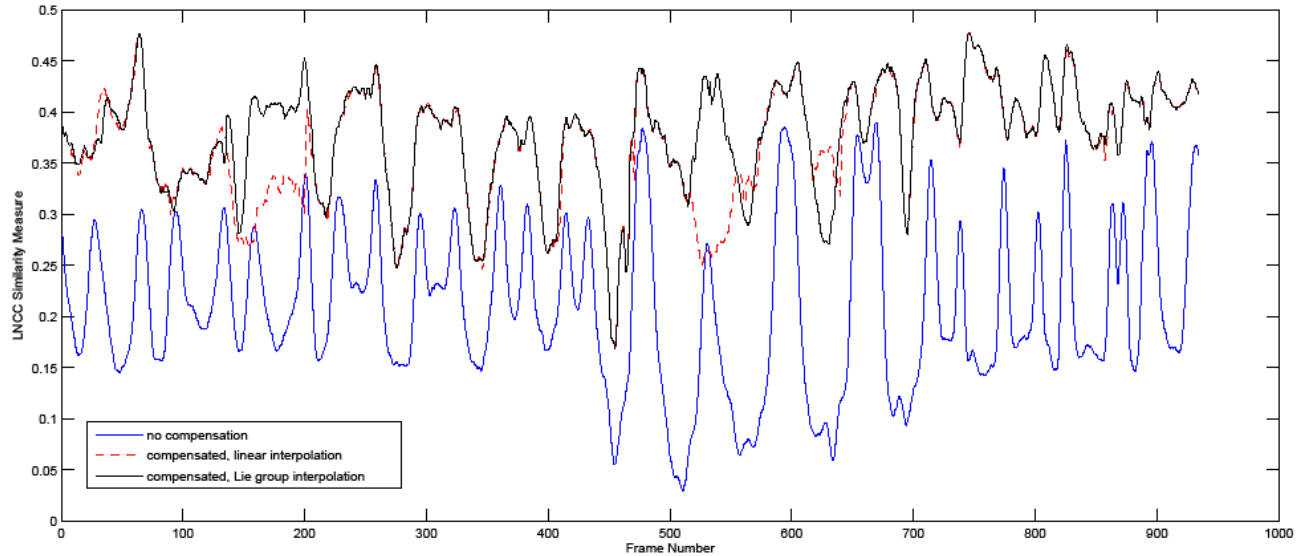


mid-inhale



First PCA vs.
surrogate signal

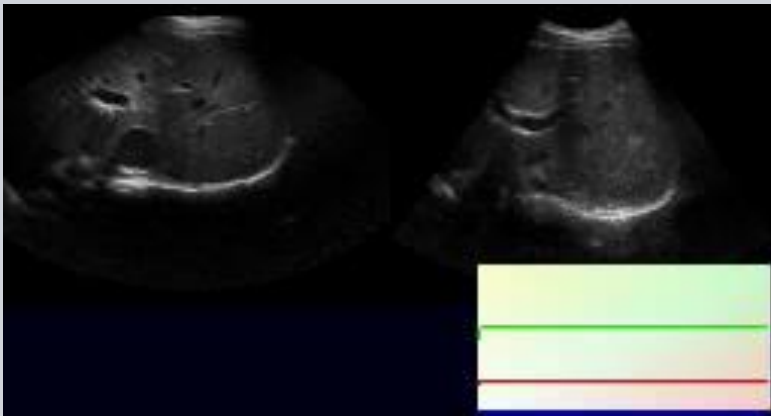
Results



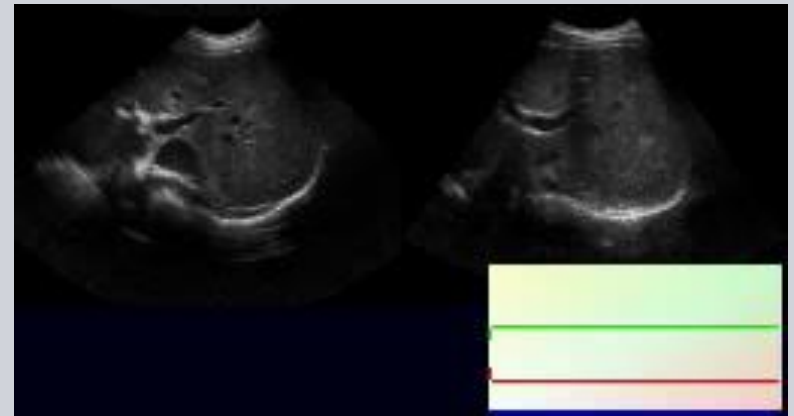
- Similarity measure results consistent
- Computation time:

	CPU LNCC	CPU SAD	GPU SAD
time / evaluation	4.8 ms	1.9 ms	1.2 ms
evaluations / frame	43	38	41
time / frame	210ms	65ms	49ms

Results (2)



Liver recording during irregular breathing



Motion-compensated sequence

- Visual results convincing, even for highly irregular breathing

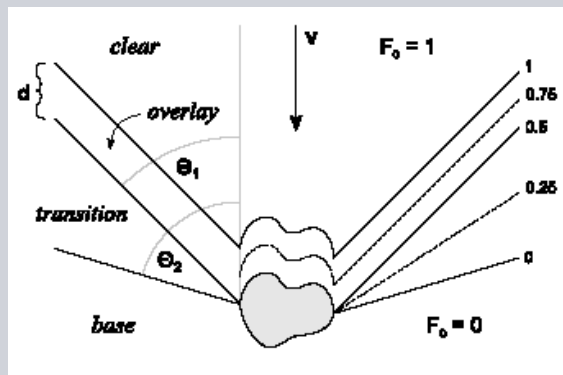
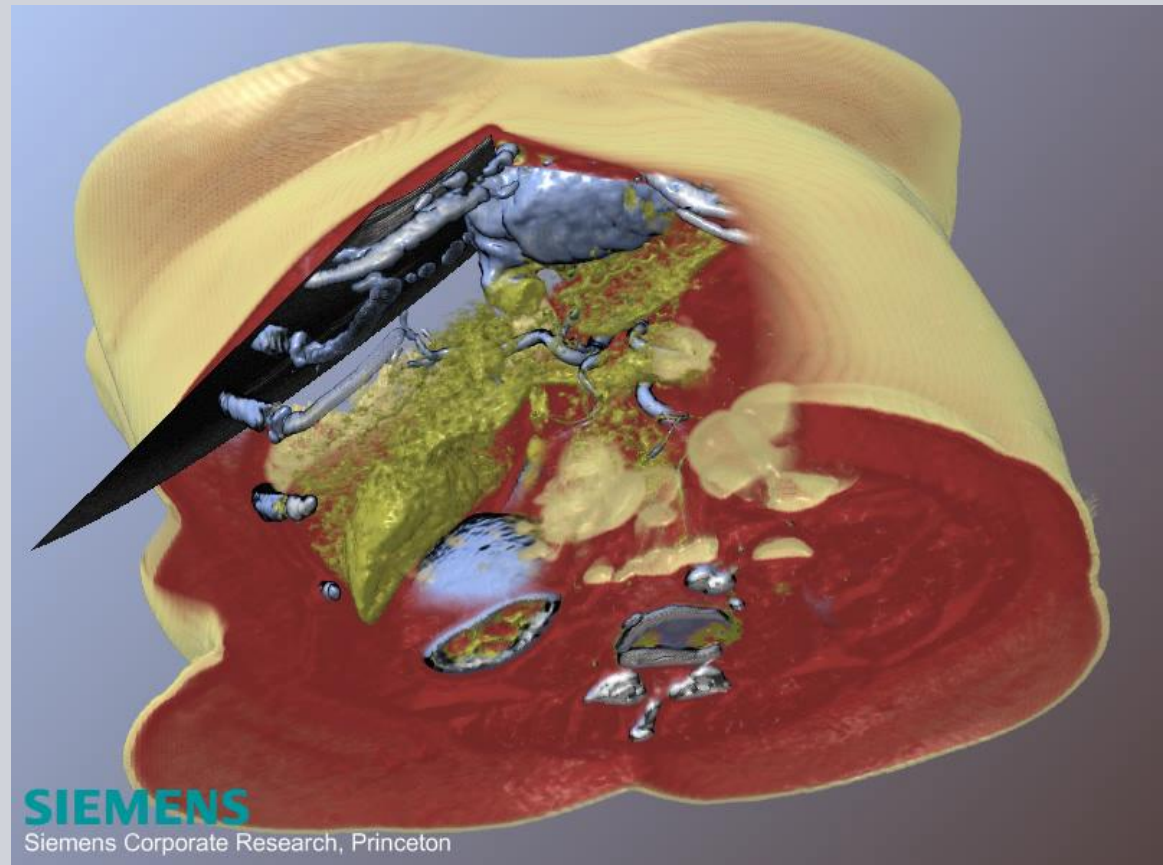
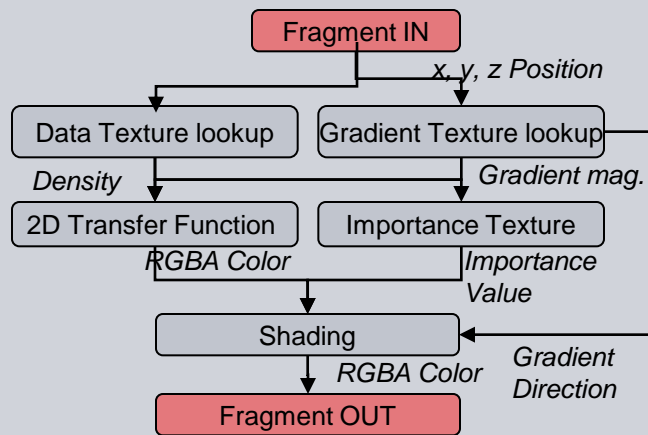
W. Wein, J-Z Cheng, A. Khamene. *Ultrasound based Respiratory Motion Compensation in the Abdomen*. IGSTI Workshop, MICCAI 2008, New York City.

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Contextual Visualization

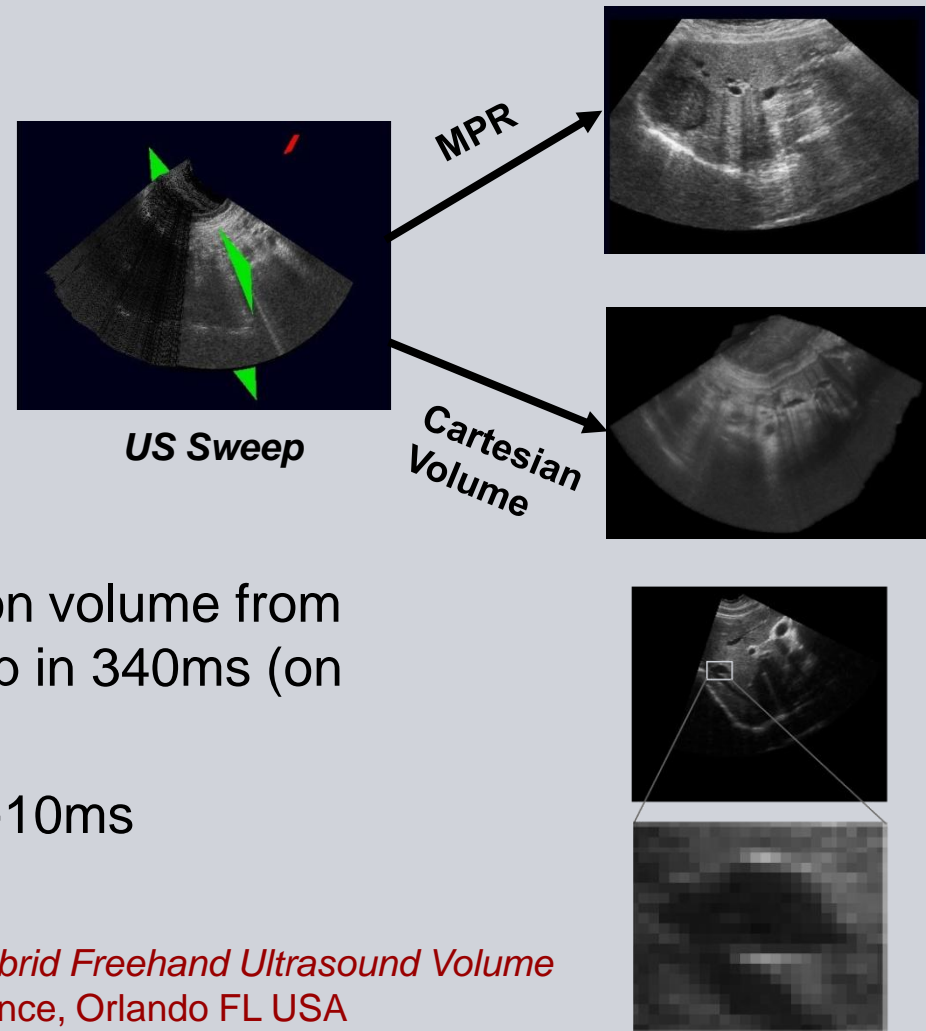
- Shows live ultrasound within dense CT volume, important vasculature emphasized in front & opaque behind ultrasound plane



M. Burns, M. Haidacher, W. Wein, I. Viola, and E. Groeller. Feature emphasis and contextual cutaways for multimodal medical visualization. In *EuroVis 2007 Proceedings*

GPU-accelerated Freehand Ultrasound Reconstruction

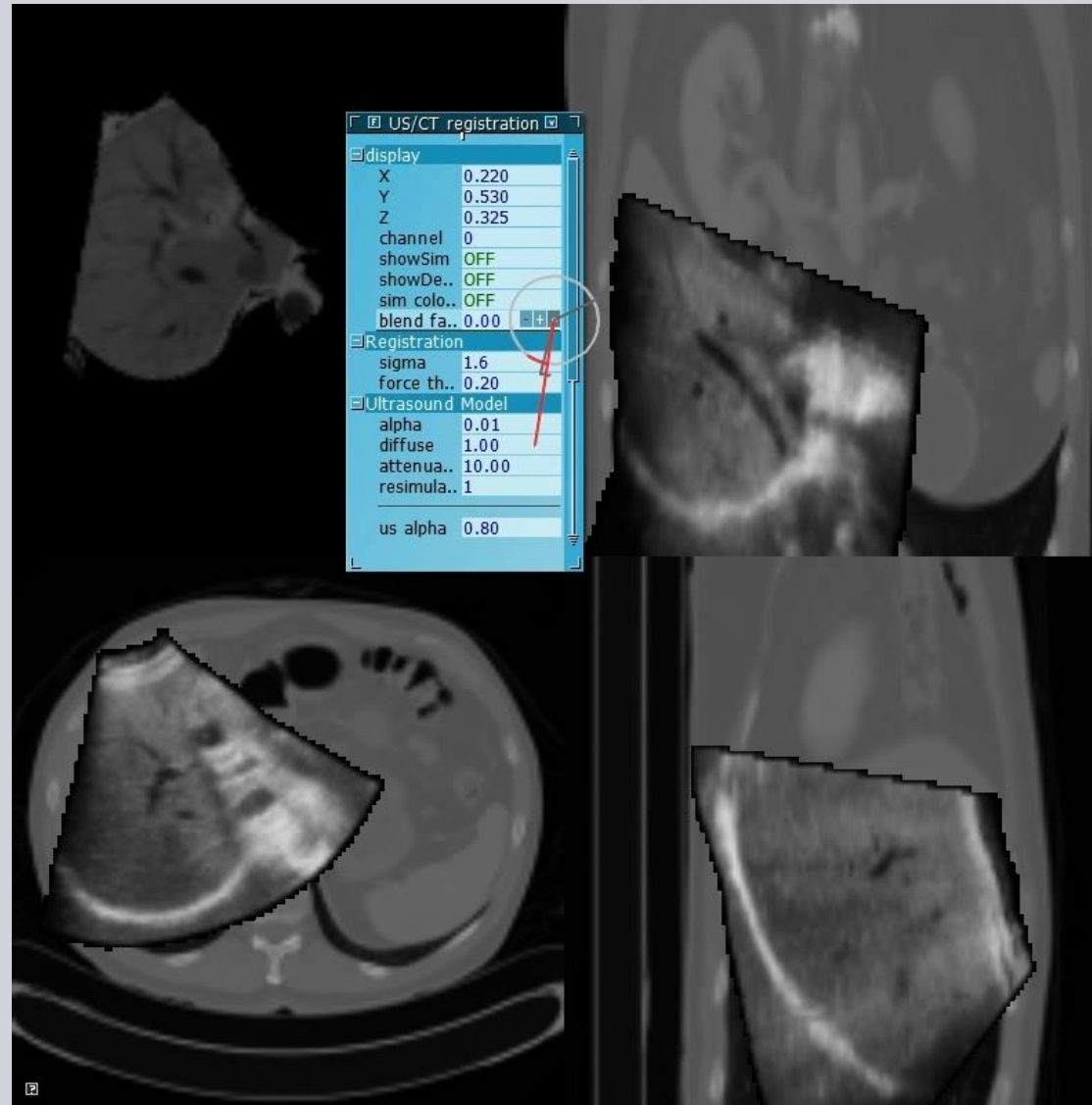
- Directly compute oblique cross-sections → improved quality
- Drawing 2D frames as quads onto reconstruction slice(s)
- Mix between forward/backward compounding
- Computes entire 256^3 reconstruction volume from dense tracked 3D ultrasound sweep in 340ms (on NVidia GeForce 8800 GTX)
- Arbitrary MPR through US sweep ~10ms



A. Karamalis, W. Wein, O. Kutter, N. Navab: *Fast Hybrid Freehand Ultrasound Volume Reconstruction*. SPIE Medical Imaging 2009 conference, Orlando FL USA

Non-linear CT-US registration

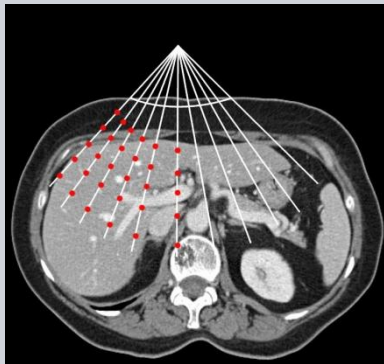
- Dense-field deformable registration based on LC^2
- Full GPU Implementation with re-simulation of ultrasound in every iteration



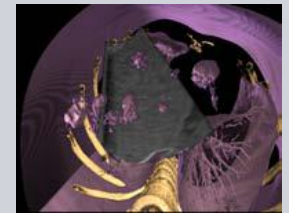
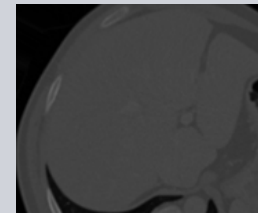
W. Wein, O. Kutter, A. Aichert, D. Zikic, A. Kamen, N. Navab. *Automatic non-linear mapping of pre-procedure CT volumes to 3D ultrasound*. ISBI conference, Rotterdam, Netherlands, 2010.

GPU-accelerated Ultrasound Simulation

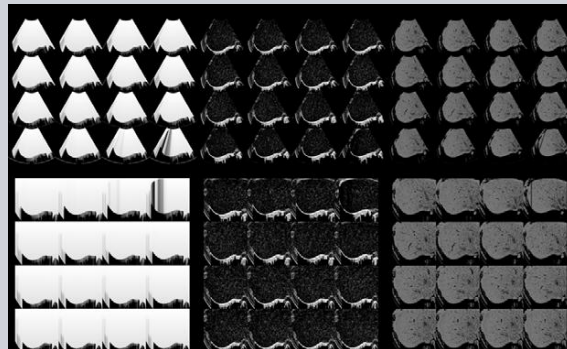
- Dense ray-based simulation of US volume from CT in ~60 ms



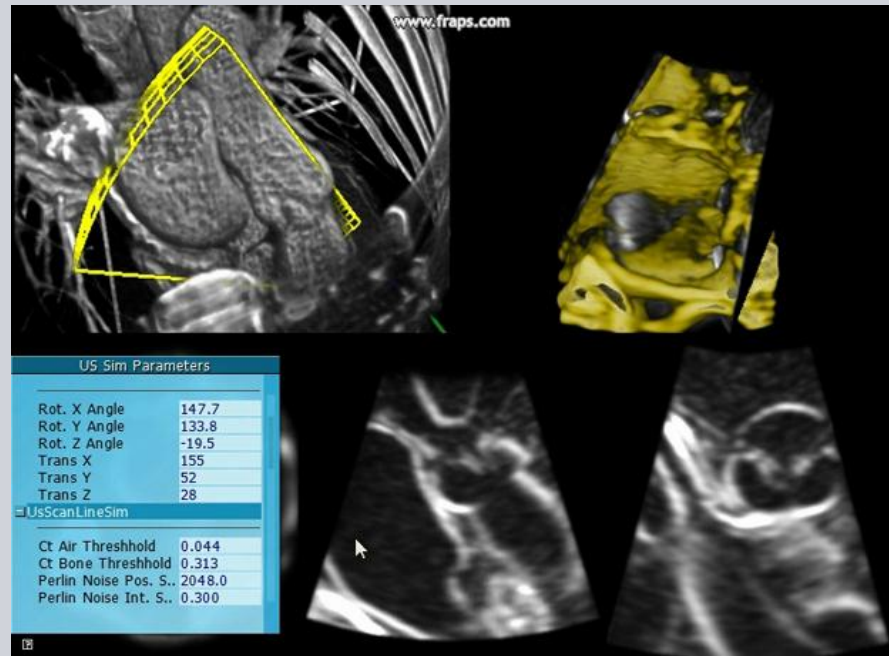
ray sampling



4D cardiac US simulation (O. Kutter)



2D texture packing



O. Kutter, A. Karamalis, W. Wein, N. Navab: *A GPU-Based Framework for Simulation of Medical Ultrasound*. SPIE Medical Imaging 2009 conference

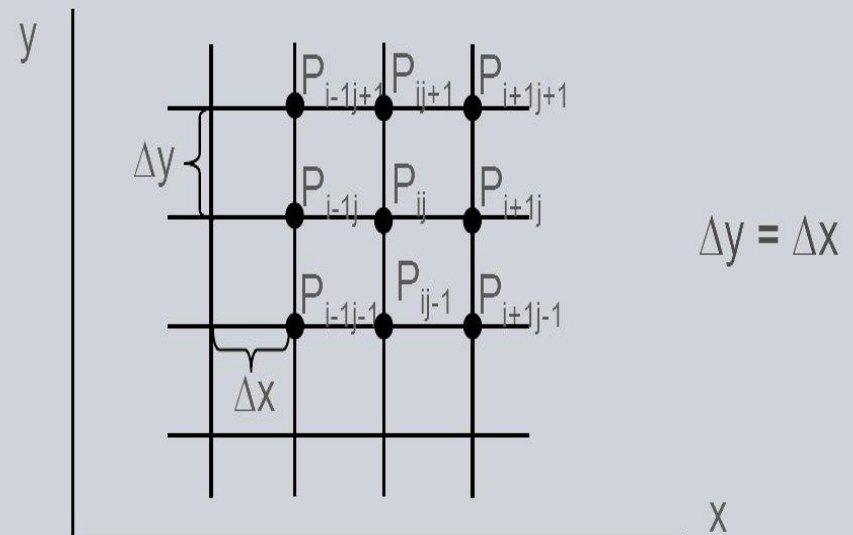
Wave-based Ultrasound Simulation

Together with Athanasios Karamalis

- Ray-based simulation does not take into account:
Diffraction, Scattering, Interference, Multiple reflection and refraction
- Solve explicitly or implicitly the wave equation for sound waves
- Current approaches are computational highly demanding
- Popular software “Field II” can take 12- 24 hours on a 32 workstation cluster for simulating a single ultrasound image

Finite-difference Time-domain (FDTD) method

- Introduced and commonly used in computational electrodynamics for solving Maxwell's time-dependent PDEs
- Further applications in computational fluid dynamics (CFD)
- Solve Partial Differential Equations:
 - Discretize domain
 - Take finite differences for partial derivatives
 - Substitute and solve for desired variable



The Westervelt Equation

- Full nonlinear wave equation for acoustic simulation
- Applications
 - Harmonic frequency simulation
 - Temperature fields simulation for focused ultrasound

$$\underbrace{\nabla^2 p - \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2}}_{T_a} + \underbrace{\frac{\delta}{c_0^4} \frac{\partial^3 p}{\partial t^3}}_{T_b} + \underbrace{\frac{\beta}{\rho_0 c_0^4} \frac{\partial^2 p^2}{\partial t^2}}_{T_c}$$

- T_a ▪ Linear lossless wave propagation
- T_b ▪ Absorption due to heat conduction
- T_c ▪ Nonlinear distortion
- p ▪ Acoustic pressure
- c₀ ▪ Speed of sound
- ρ₀ ▪ Ambient density of mass
- β ▪ Nonlinear coefficient
- δ ▪ Diffusivity of sound

The Westervelt Equation (2)

- Discretizing the 2D Westervelt equation

$\nabla^2 p$ Fourth order central differences

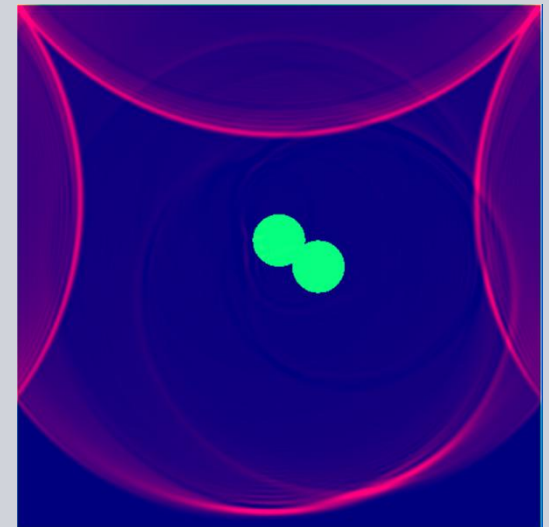
$\frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2}$ Second order central differences

$\frac{\delta}{c_0^4} \frac{\partial^3 p}{\partial t^3}$ Second order backward differences

$\frac{\beta}{\rho_0 c_0^4} \frac{\partial^2 p^2}{\partial t^2}$ Second order backward differences

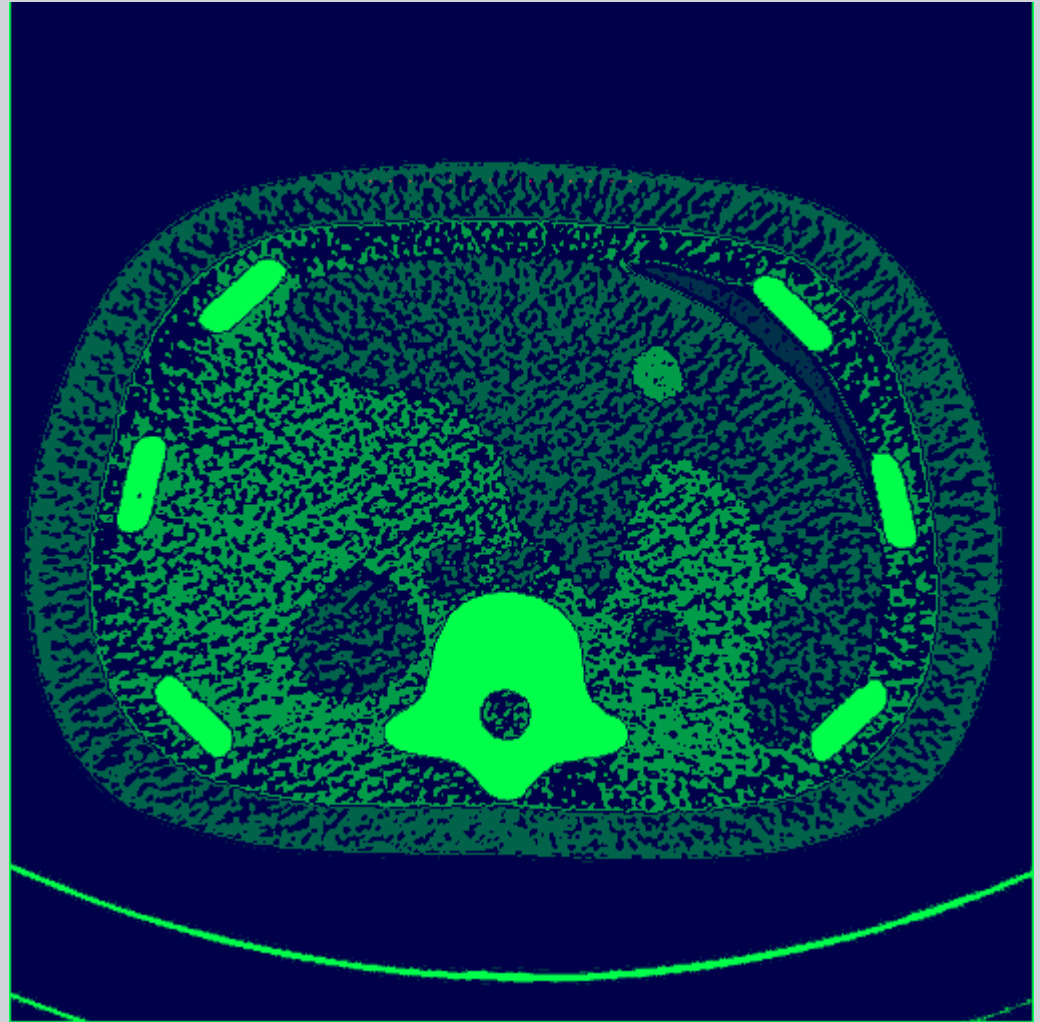
- Results

- Explicit solution for the next time-step
- Based on the 6 previous time-steps
- Non-linear distortion and absorption



Westervelt FDTD - Results

- Performance:
~1290 time-step evaluations/s
for 512x512 sampling grid, on
NVIDIA GeForce 8800 GTX
- Linearly aligned point sources
- Manually segmented CT
phantom dataset
- Medium speed variations
600, 1555, 1560 and 4080 [m/s]

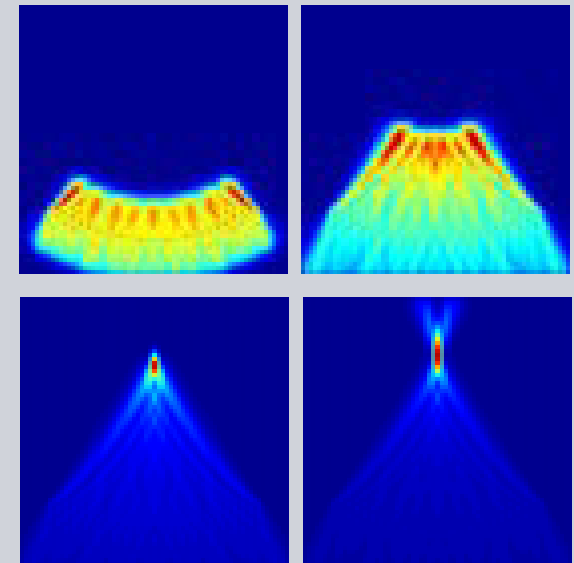


Challenges and future work

- Absorbing boundary conditions for mesh boundaries
- Segmentation/labeling of datasets for property assignment
- Variety of excitation pulses (sinusoidal, phase delayed; currently Dirac impulse)
- Pipeline from RF data to final ultrasound image
- Validating simulation with real measurements

Possible Application – High Intensity Focused Ultrasound (HIFU)

- MR guided HIFU demonstrates potential
- Use simulation to guide and predict therapy
- Temperature field simulation in thermoviscous fluids was the first step



A. Karamalis, W. Wein, N. Navab. Fast Ultrasound Image Simulation using the Westervelt Equation. MICCAI conference, Beijing, China, September 2010

Agenda

- Challenges of 3D Freehand Ultrasound
- Image-based CT-Ultrasound Registration
- Real-time respiratory motion compensation
- Visual Computing / GPU Algorithms
 - Visualization
 - 3D Freehand Ultrasound Reconstruction
 - Ultrasound Simulation
- Clinical Applications
 - Liver RFA
 - Prostate Biopsy
 - Cardiac EP Procedures
- Conclusion

Clinical Application – Interventional Fusion

- Biopsies and Radiofrequency Ablation in the Liver and Kidney
- Based on CT Diagnosis & Planning
- Interventional Navigation by CT or Ultrasound:

CT: not real-time,
interruption for imag.

US: long training, no
pre-op information



→ Combining US Navigation with
planning information from CT!



Targeted Prostate Biopsy

- Project with MR/SP/CAS

Setup

TRUS probe with sensor

Tracking field generator

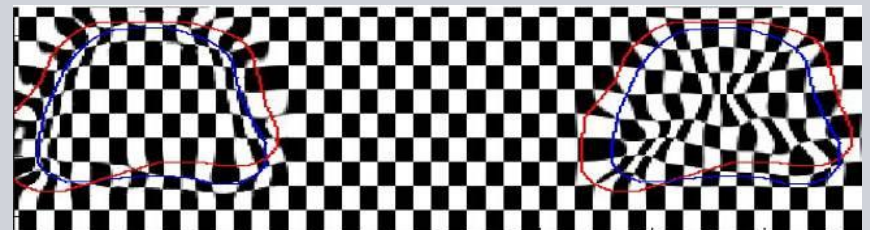


Workstation

MRI-TRUS side-by-side

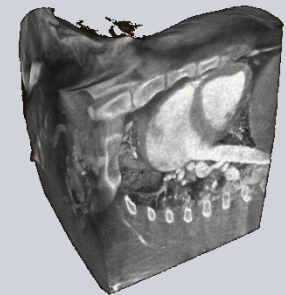
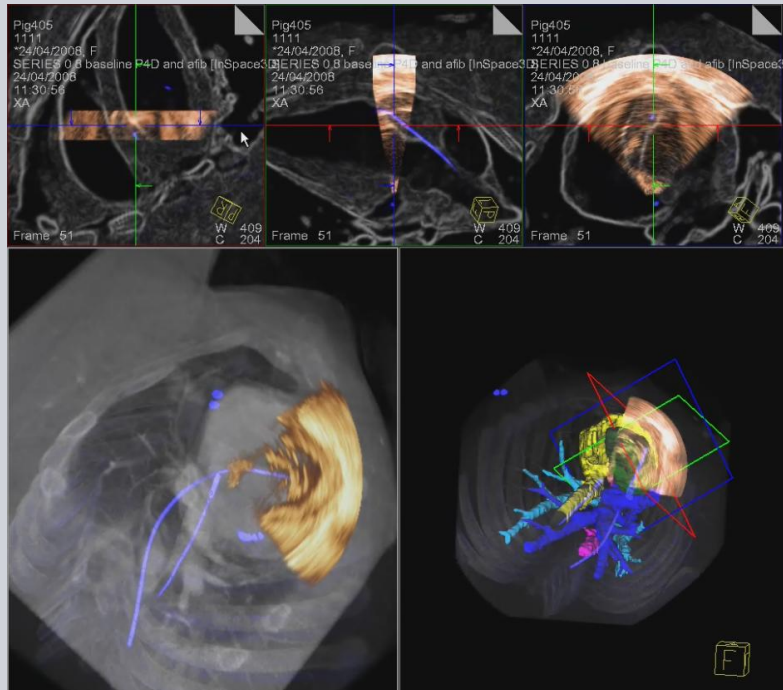
Weiss C., Seitz M., Herrmann K.A., Graser A., Kiefer B., Requardt M., Fehre J., Nanke R., Diallo, M., Kamen, A., Wein, W.: MR-US Fusion for Targeted Prostate Biopsy. ISMRM 2010 conference

Boundary-based deformable registration

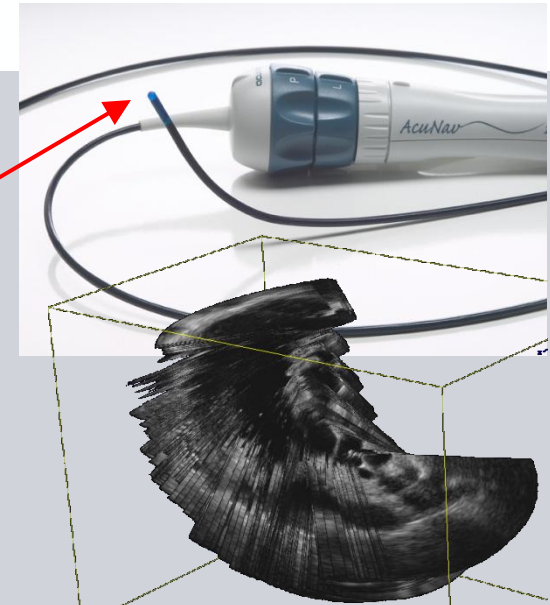


Clinical Application - ICE-CT Fusion

- Fusion of Intracardiac Echography (ICE) with C-Arm CT for Electrophysiological Procedures
- Tracking sensor integrated within ICE catheter



DynaCT volume



whole pig heart sweep



validation based on manual segmentation

Y. Sun et al. in MICCAI 2007 conference

W. Wein et al.: Towards Guidance of Electrophysiological Procedures with Real-time 3D Intracardiac Echocardiography Fusion to C-arm CT. In MICCAI 2009 Conference, London UK

Agenda

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Conclusion - Take-away Messages

- Ultrasound challenging, dynamic modality
- Precise modeling of imaging physics and uncertainties important
- Research frontiers: Tracking (sensor fusion), multi-modality registration, motion compensation, visualization, workflow
- Exploiting concurrency is mandatory
- Vision: Image and sensor data feeds are used in real-time to build and update patient-specific model
- Close feedback loop with physicians is crucial – details matter

Thanks!

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