Three-Dimensional Ultrasound Mosaicing

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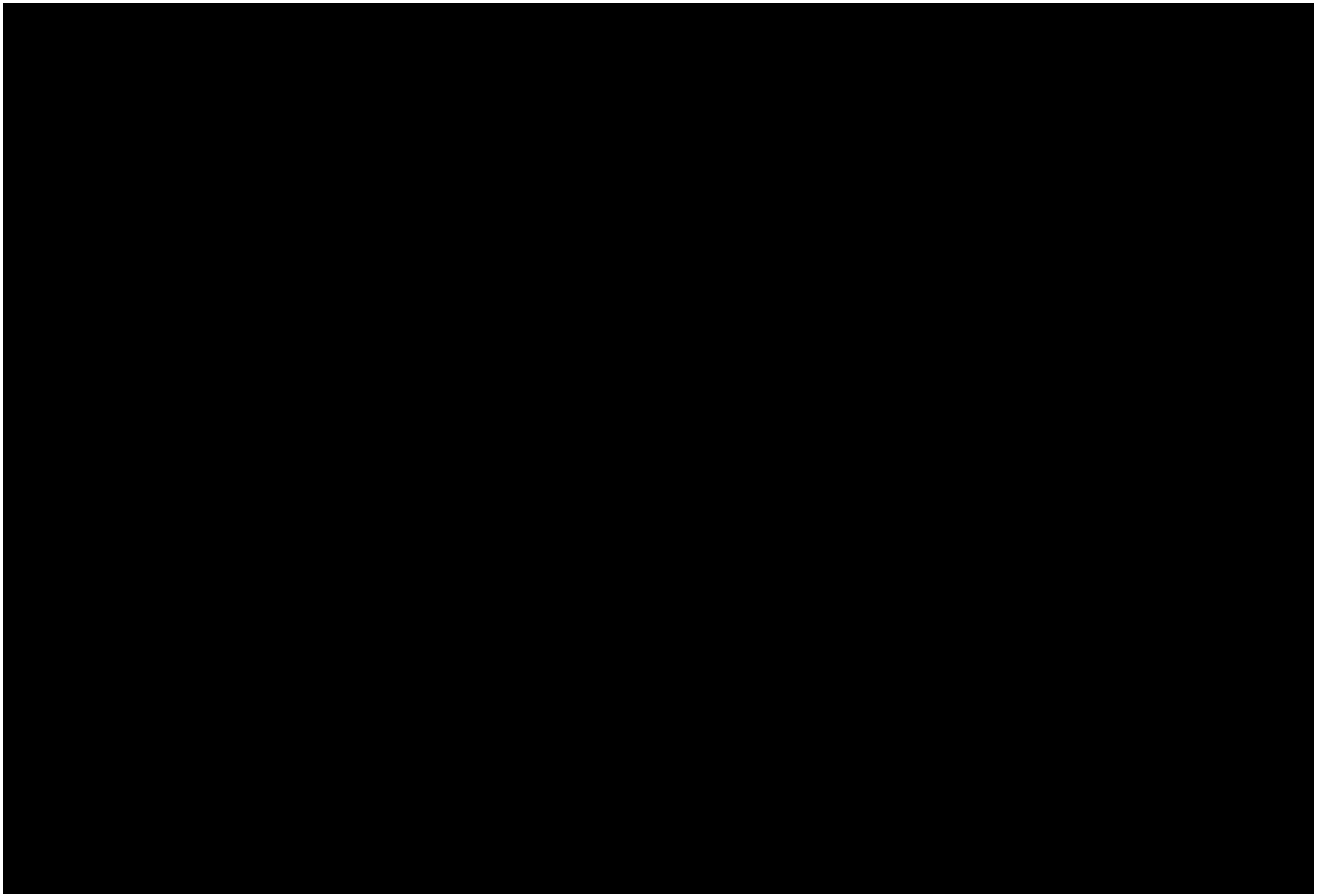
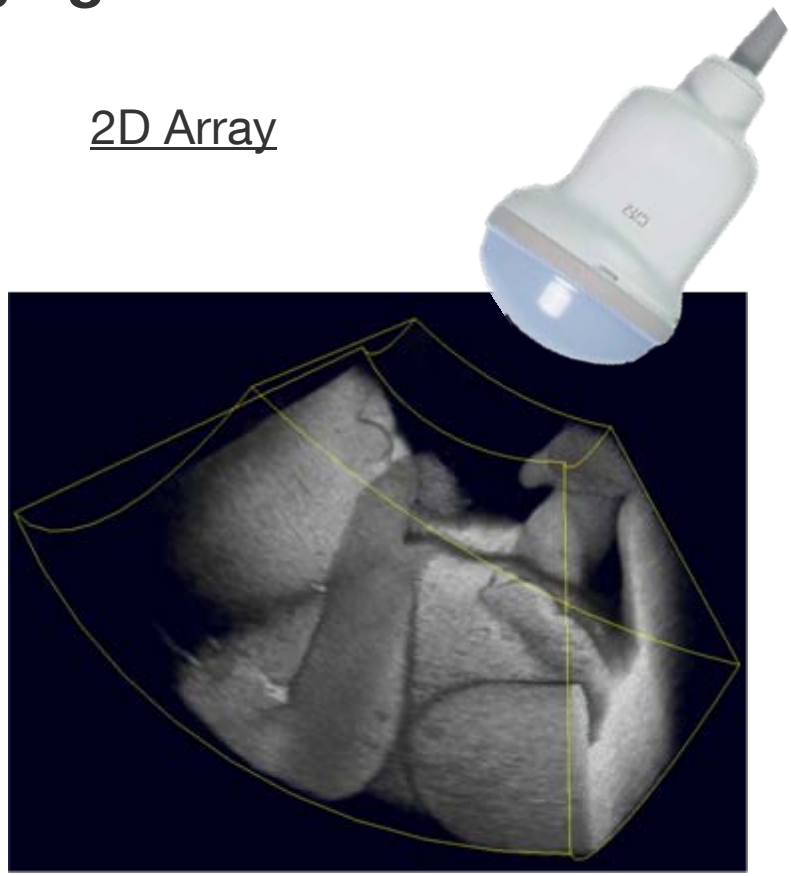


Moving from 2D to 3D US Imaging

1D Array

3D with: - Freehand US
- Wobbler probes

2D Array

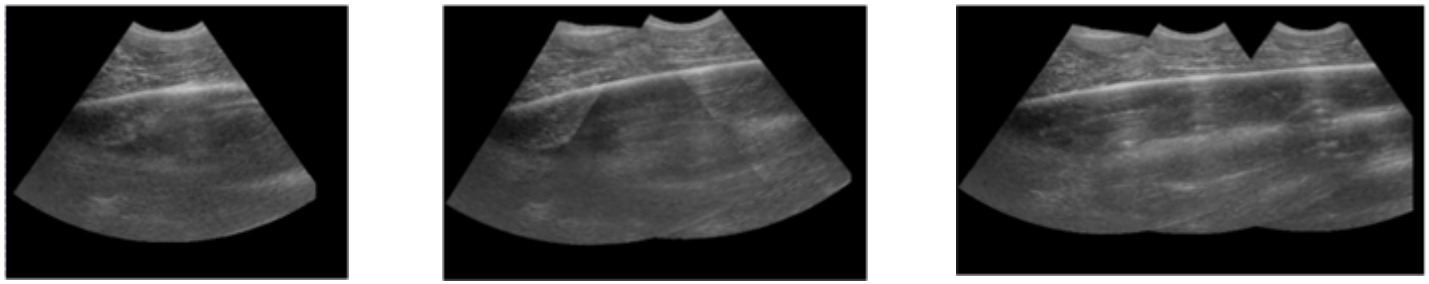


CMUT Technology

Clinical Value of Ultrasound Mosaicing

Extended Field-of-View and **Quality Improvement:**

- Measuring spatial relationship among large structures – *(Kim, 2003)*
- Sonographers have the flexibility to visualize anatomical structures from a variety of different angles – *(Peetrons, 2002; Leung, 2005)*
- Size and distance measurements of large organs – *(Ying, 2005)*
- Individual structures within a broader context can be identified by having an image of the whole examination area – *(Dietrich, 2002)*
- Specialists not used to ultrasound can better understand the spatial relationships of anatomical structures – *(Heinrich, '03)*



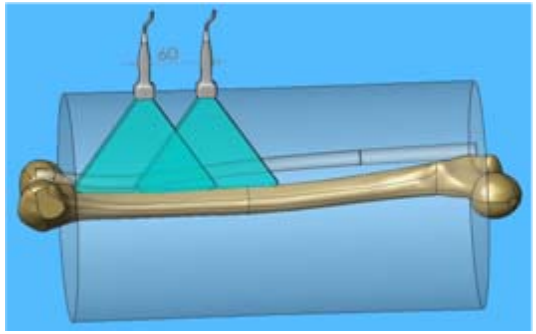
Agenda

1. **Mosaicing Strategies**
2. Similarity Measures
3. Experiments & Conclusion

Problem Statement

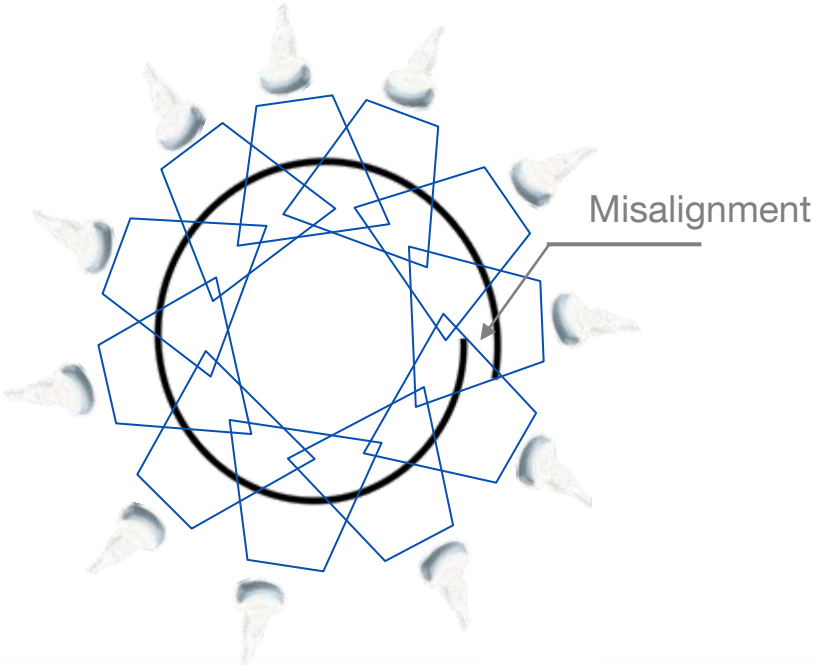
Proposed 3D mosaicing techniques by *(Gee, 2003)* and *(Poon, 2006)* use a **sequence of pairwise registrations**

Partial Overlap:



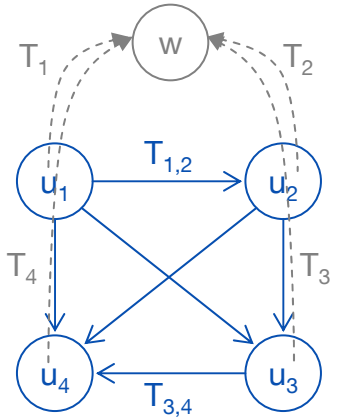
➡ High demands on the overlap invariance of similarity measures

Accumulation errors:

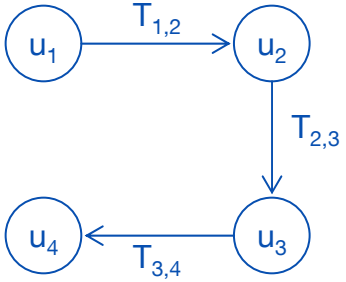


Mosaicing Strategies – Multiple Image Alignment

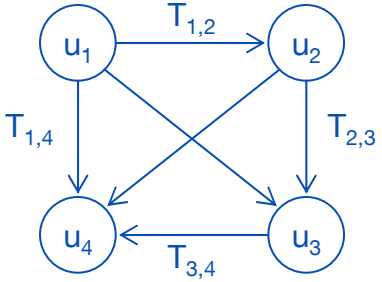
- Having n Images u_1, …, u_n
- Pairwise Transformations $T_{i,j}$ from intensity-based rigid registration
- Global Transformations T_1, …, T_n



Sequential Pairwise Registration



Complete Pairwise Registration

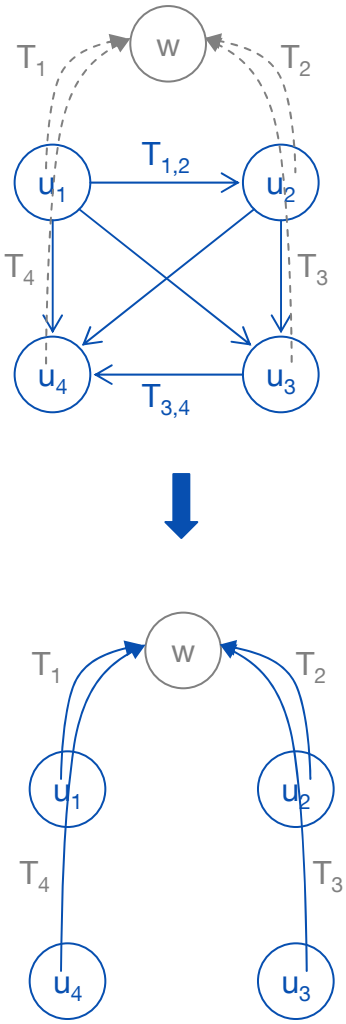


➡ Lie Group based Normalization *(Vercauteren, MICCAI 2005)*

Simultaneous Registration

- Registration of all images at the same time
  - Multivariate Similarity Measures
  - Parameter Space: n · 6
- Adressing the mentioned problems
  - Accumulation errors are dealt with intrinsically
  - Better conditioned costfunction:
    - Overlap
    - Viewing angle dependent US images
- Increasing Computational Complexity
  - Higher dimensional parameter space
  - Evaluation of cost function more expansive

- **Semi-Simultaneous** Registration
  - Multivariate Similarity Measure
  - Moving one image at a time



Mosaicing Strategies

	Sequential PW	Complete PW	Semi-Simultaneous	Full-Simultaneous
Optimization	6	6	6	$n \cdot 6$
Similarity	Bivariate	Bivariate	Multivariate	Multivariate
Overlap	Sequence	All	All	All

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Similarity Measures

- Maximum likelihood estimation to model registration mathematically
- Imaging setup

$$u(x) = f(v(T(x))) + \varepsilon$$

u, v : images
ε : Gaussian noise
f : intensity mapping

- Negative log-likelihood function

$$\begin{aligned} -\log \mathcal{L}(T, \varepsilon, f) &= -\log P(\varepsilon = u - f(v^{\downarrow})) \\ &= -\log P(u|v, T, \varepsilon, f) \end{aligned}$$

$v^{\downarrow} = v(T(.))$

- Derivation of SSD, NCC, CR, and MI *(Viola 1995, Roche 2000)*

Extension of Likelihood Function to Multiple Images

1. Summed-Up Bivariate Extension

$$
\begin{aligned}
-\mathcal{L}(\mathcal{T}) &= -P(u_1|u_2,\ldots,u_n,\mathcal{T},\vec{f},\vec{\varepsilon}) \\
&= -\prod_{i=2}^{n} P(u_1|u_i,T_i,f_i,\varepsilon_i)
\end{aligned}
$$

$u_1,\ldots,u_n$: images
$\varepsilon_1,\ldots,\varepsilon_n$: Gaussian noises
$f_1,\ldots,f_n$: intensity mappings

$$\mathcal{T} = \{T_1,\ldots,T_n\}$$

$$
-\log(\mathcal{L}(\mathcal{T})) = -\sum_{i=2}^{n} \boxed{\log P(u_1|u_i,T_i,f_i,\varepsilon_i)}
$$

Bivariate formula

Semi-Simultaneous: $\sum_{i=2}^{n} \mathrm{SM}(u_1,u_i)$

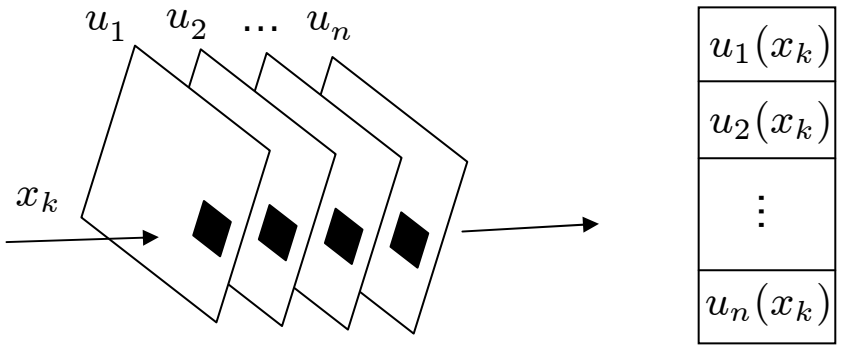
Full-Simultaneous: $\sum_{i\neq j} \mathrm{SM}(u_i,u_j)$

Extension of Likelihood Function to Multiple Images

2. Voxel-wise extension

$$
\begin{aligned}
-\log(\mathcal{L}(\mathcal{T})) &= -\log P(u_1, u_2, \ldots, u_n, \mathcal{T}) \\
&= -\sum_{x_k \in \Omega} \log P^k(u_1(x_k), u_2(x_k), \ldots, u_n(x_k), \mathcal{T})
\end{aligned}
$$

- Independent but not identical distributed coordinate samples
- Allows for varying numbers of overlapping images
- First applied to medical imaging by *Zöllei, 2005*



Summary – Multivariate Similarity Measures

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

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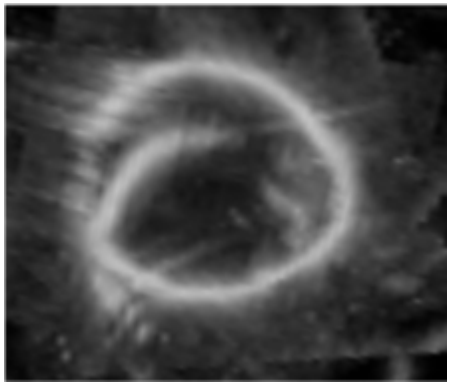
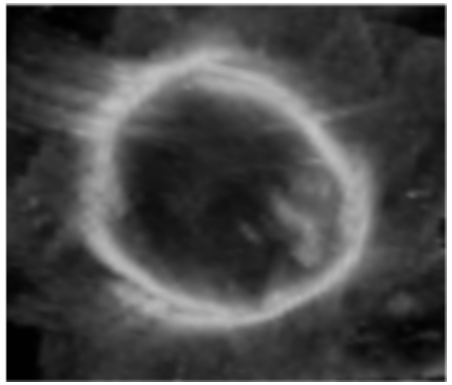
3. **Experiments & Conclusion**

Experiments on Clay Model

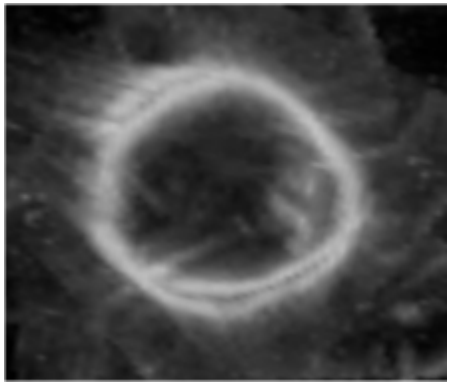
Pairwise



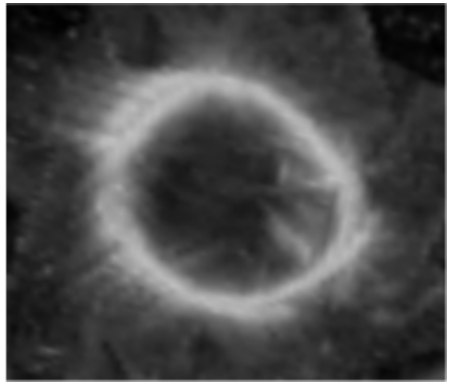
Lie normalization

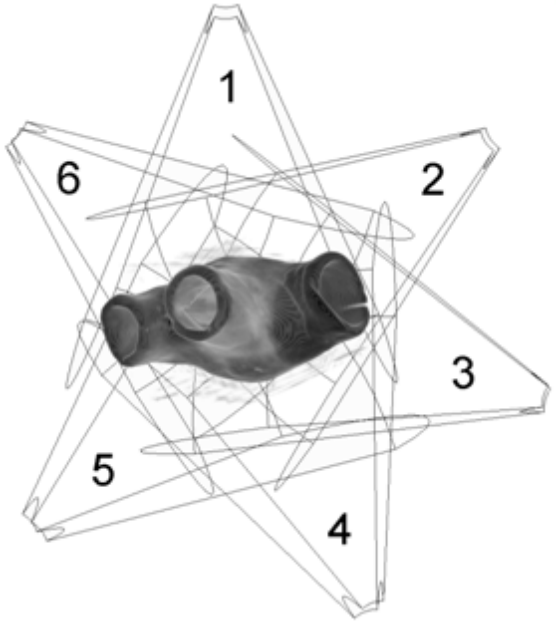


Semi-Simultaneous



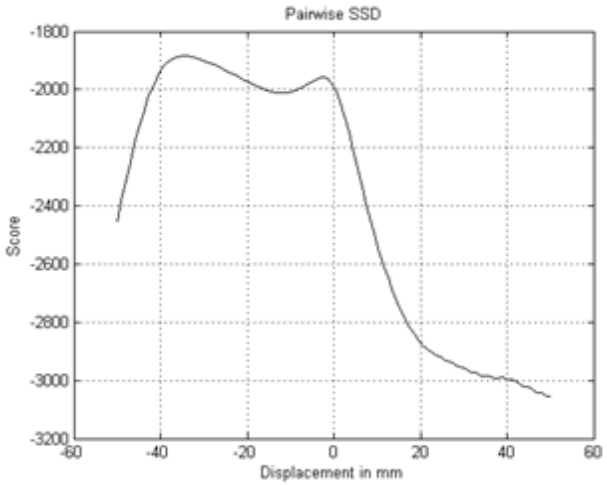
Full-Simultaneous

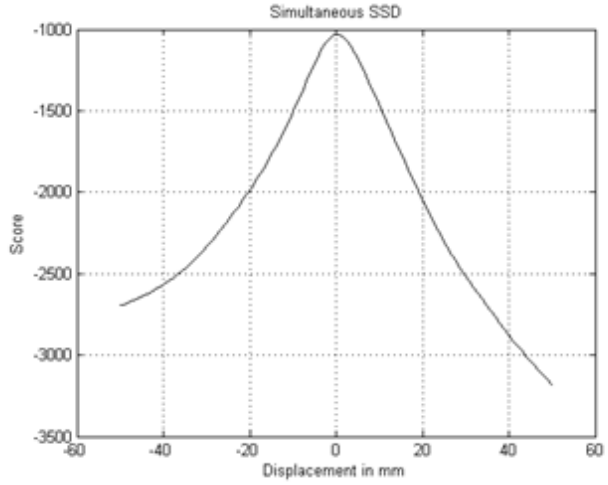


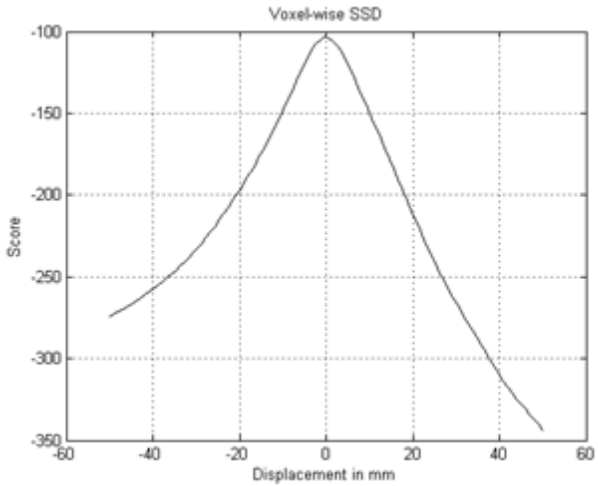


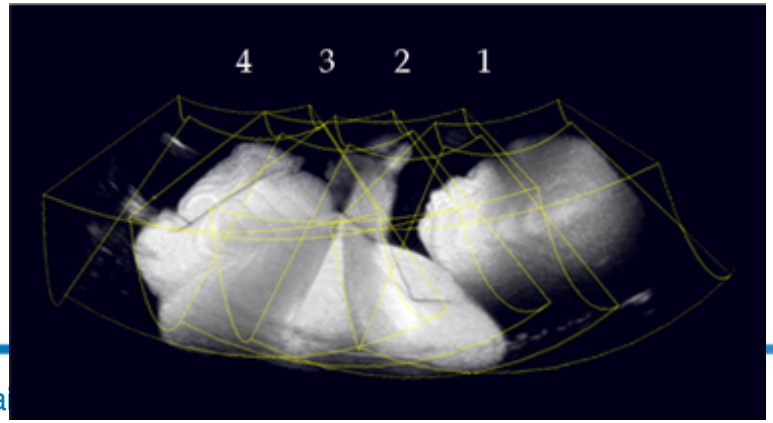
Experiments on Baby Phantom

- Similarity Plot: moving image 2 along the cranio-caudal axis

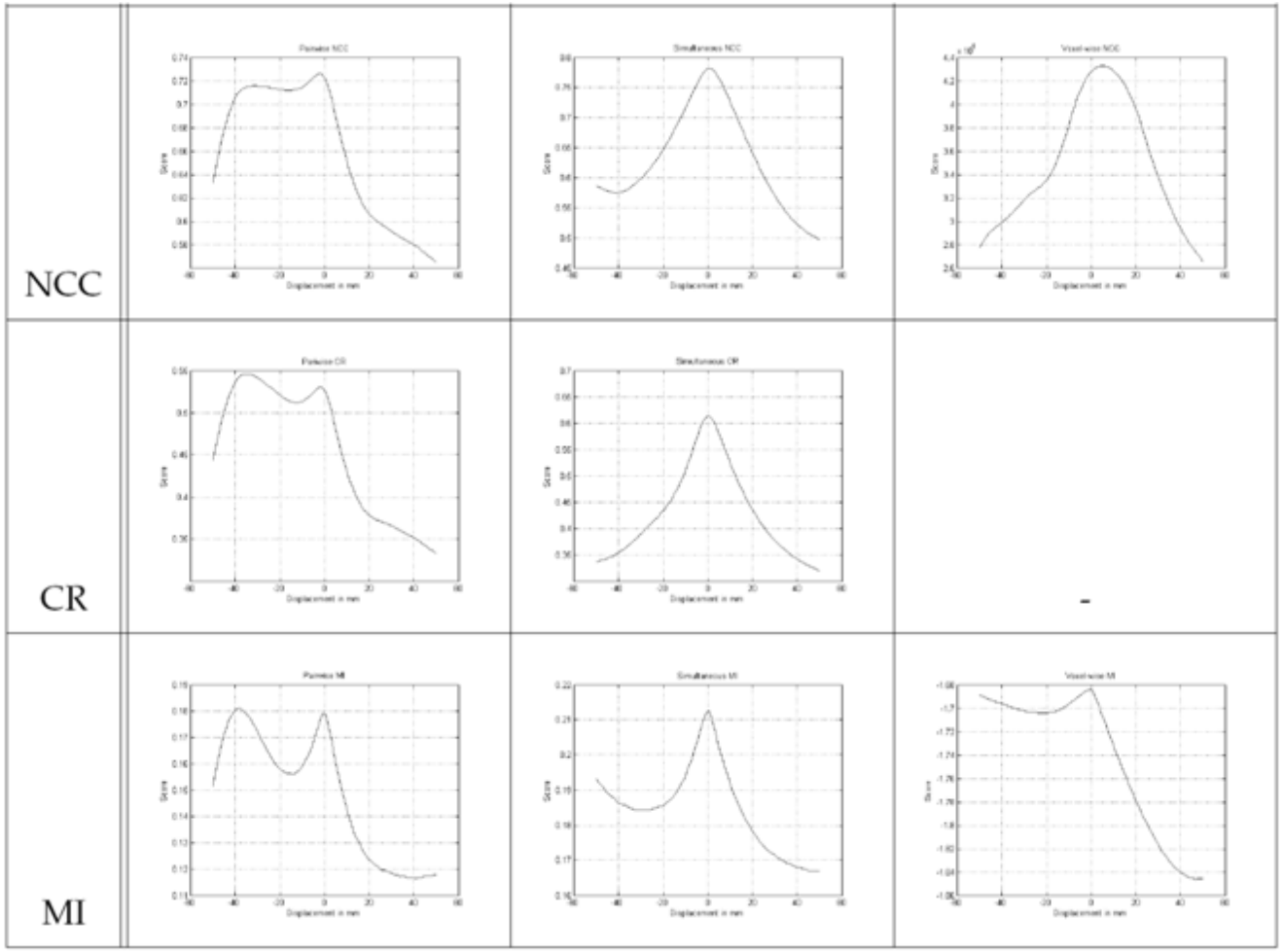






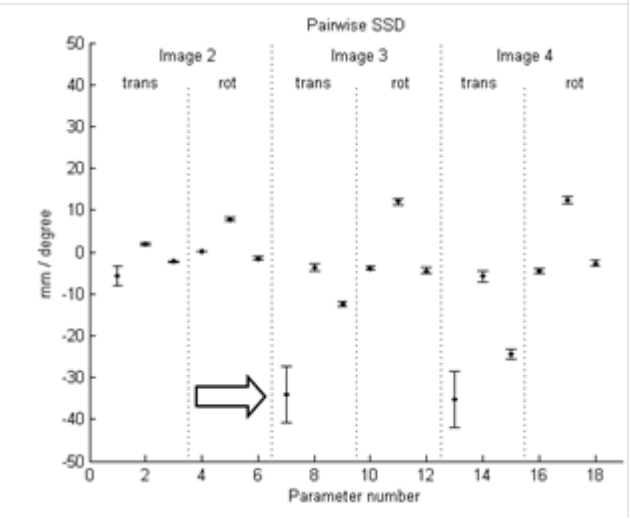


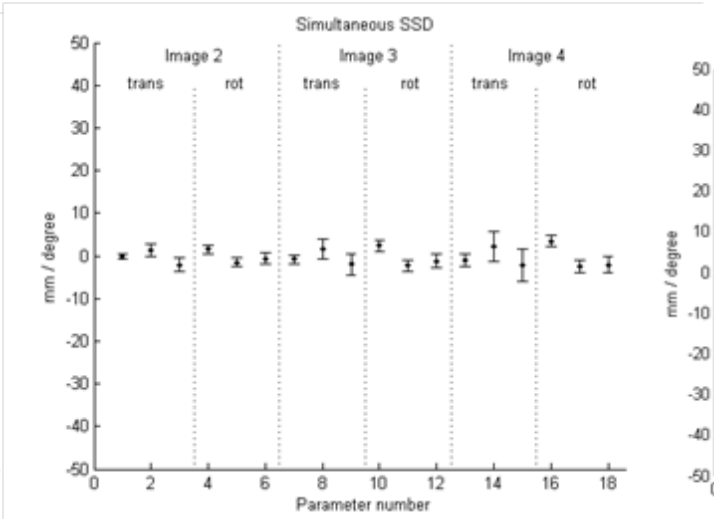
Experiments on Baby Phantom

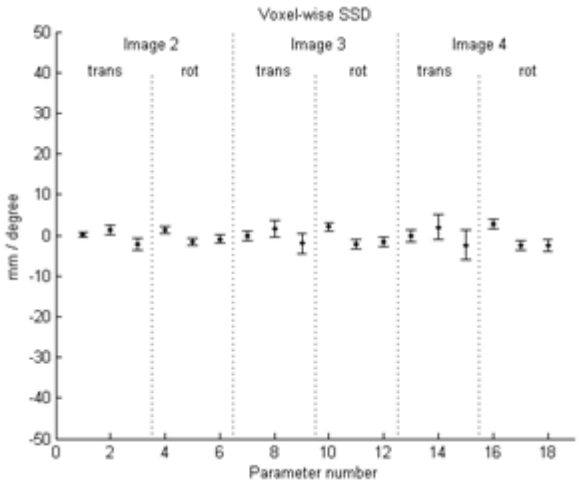


Experiments on Baby Phantom

- Random Registration Study
  - 4 images
  - Up to ± 20 mm/degree random initial displacement
  - 100 registrations
  - Sum of Squared Differences
  - Plotting mean and standard deviation





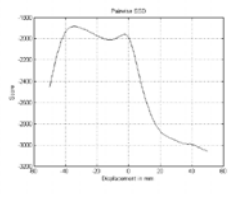
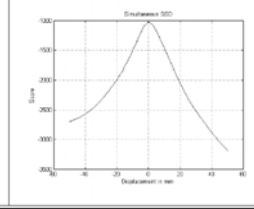
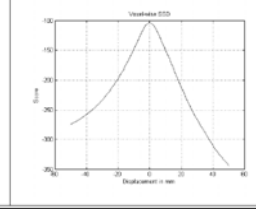


Conclusion

- Ultrasound mosaicing as multiple image alignment
- Proposal of specific registration strategies for mosaicing
- Deduction of multivariate extensions for similarity measures under usage of a maximum likelihood framework
- Experiments show the superior performance of proposed strategies

	Sequential PW	Complete PW	Semi-Simultaneous	Full-Simultaneous
Optimization	6			
Similarity	Bivariate			
Overlap	Sequence			

	Pairwise	Semi-Simultaneous	Full-Simultaneous	Voxel-Wise
SSD	$\mathbb{E}[(u - v^{\downarrow})^2]$	$\sum_{i=2}^{n} \omega_{1,i} \mathbb{E}[(u_1$		
NCC	$\mathbb{E}[\tilde{u} \cdot \tilde{v}^{\downarrow}]$	$\sum_{i=2}^{n} \omega_{1,i} \mathbb{E}[\tilde{u}_1$		
CR	$\frac{\mathrm{Var}[\mathbb{E}(u\|v^{\downarrow})]}{\mathrm{Var}(u)}$	$\sum_{i=2}^{n} \omega_{1,i} \frac{\mathrm{Var}[\mathbb{E}($}{\mathrm{Var}($}		
MI	$\mathrm{MI}(u, v^{\downarrow})$	$\sum_{i=2}^{n} \omega_{1,i} \mathrm{MI}(u$		

	Pairwise	Full-Simultaneous	Voxel-Wise
SSD			

Publications

Further information: Diploma Thesis
http://campar.in.tum.de/Students/DaWachinger

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