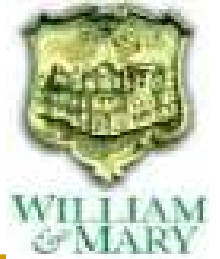
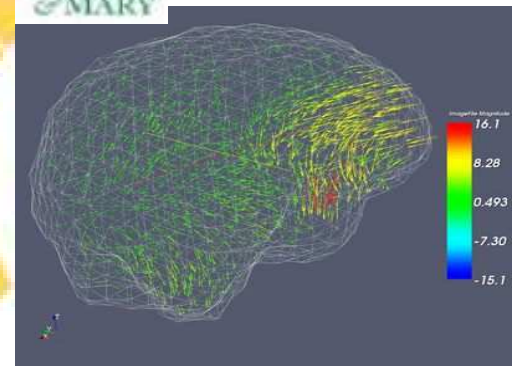


Near Real-Time Non-Rigid Registration of pre-operative and intra-operative MRI for Image Guided Neurosurgery



N. Chrisochoides, A. Fedorov, A. Kot (College of William and Mary)

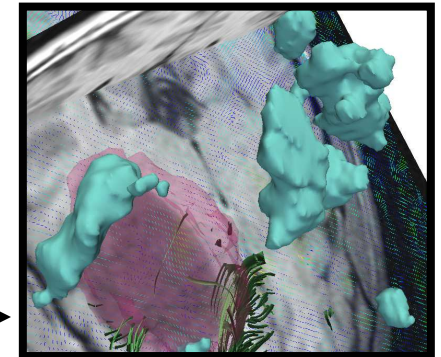
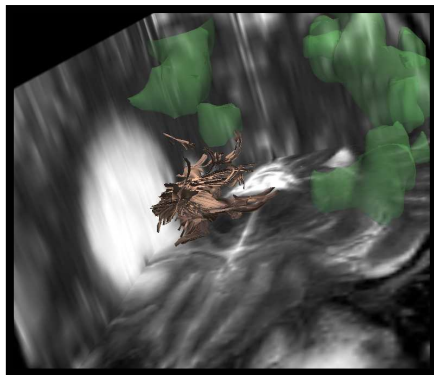
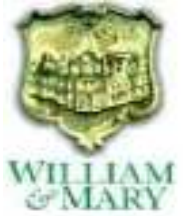
N. Archip, P. Black, O. Clatz, A. Golby, R. Kikinis, S. Warfield (Harvard Medical School)



We acknowledge Stephen Whalen, Dan Katcher, Ferenc Jolesz, and Tom Crockett for their help in conducting this study

NSF grants: NGS-0203974 and ITR-0426558 and John Simon Guggenheim Foundation

Problem: Brain shift



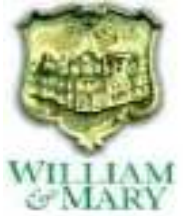
intra-operative scanners can track deformation

Problems:

- Image quality is low compared to pre-operative data
- Time consuming to acquire data like fMRI during surgery using low (0.12T) to medium (0.5T) field magnets.

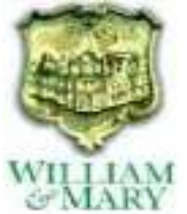
Non-Rigid Registration: wrap pre-operative data into intra-operative images

Requirements



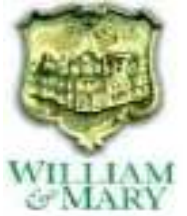
- q **Accuracy:** transformation needs to be precise
- q **Robustness:** the registration should work with poor quality image (0.5T MRI)
- q **Speed:** it should not take more than 1 min to complete the registration.

Outline



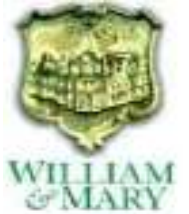
- n Overview of Registration Method
 - q Physics based model -- Approximation
 - n *Outliers*
 - n Distributed and Grid Computing
 - q Performance Improvements
 - q Accuracy
 - n Comparison with State-of-the-art
 - q Summary of data from 11 patients
 - n Summary and Future Work
-

Pre-processing



- n Segment the brain, ventricles, and tumor in pre-operative MRI (1.5T)
- n Perform rigid registration with the first intra-operative image (before dura mater opening)
- n Generate the patient-specific biomechanical model of the brain using segmented data
- n Select blocks in pre-operative segmented image (w/o tumor segmentation)

Formulation



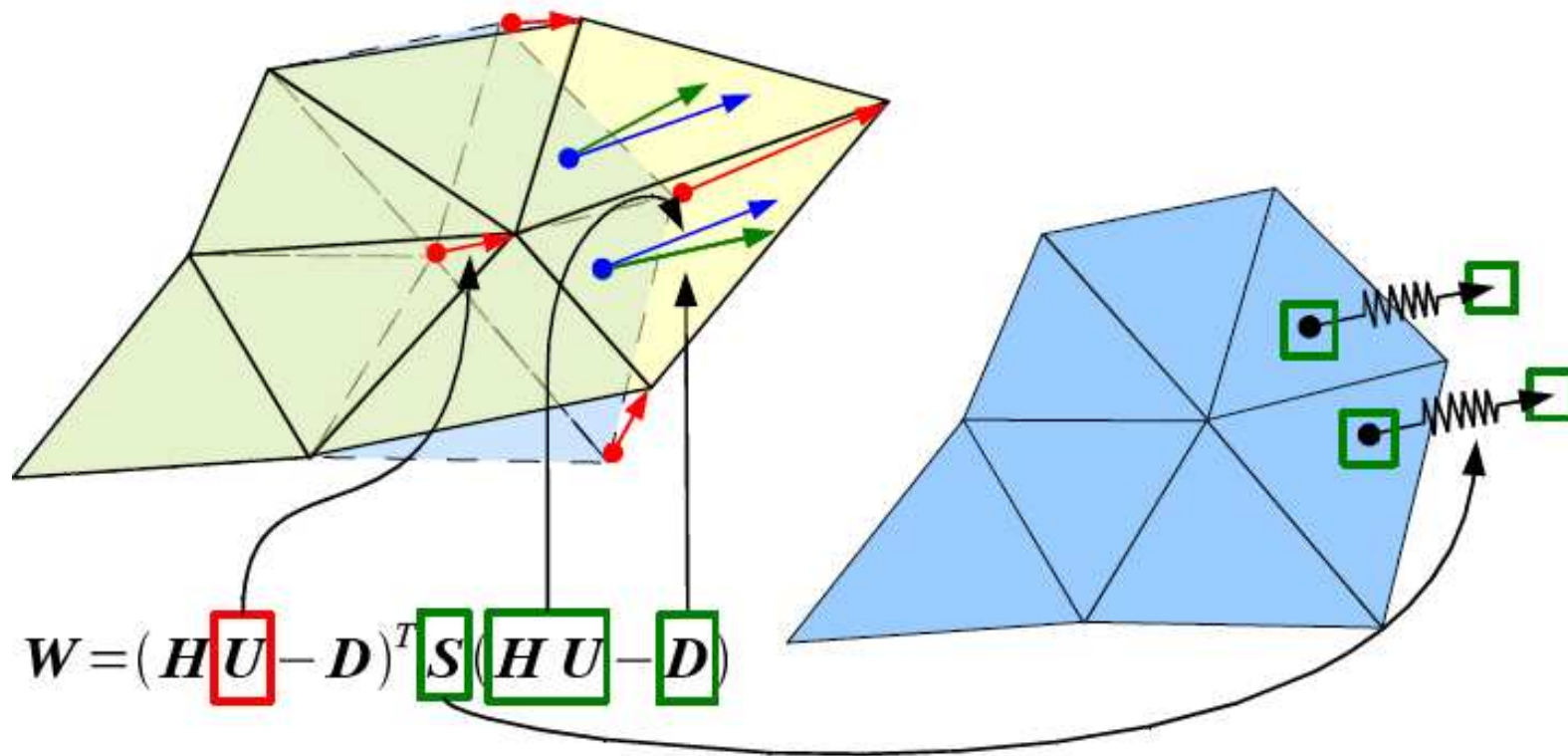
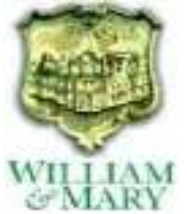
- n Elastic matching of two images I_1 and I_2
 - q Energy minimization procedure with two terms:
 1. **Mechanical energy** modeled by the physical properties of the depicted object to be deformed
 2. **Matching energy** modeled as the squared differences of images I_1 and I_2

$$\frac{1}{2} \int_{\Omega} \boldsymbol{\sigma}^T \boldsymbol{\epsilon} \, d\Omega + \frac{1}{2} \int_{\Omega} (I_1(\mathbf{x} + \mathbf{u}) - I_2(\mathbf{x}))^2 \, d\Omega$$

$\boldsymbol{\epsilon}$ is the strain tensor and $\boldsymbol{\sigma}$ the stress tensor

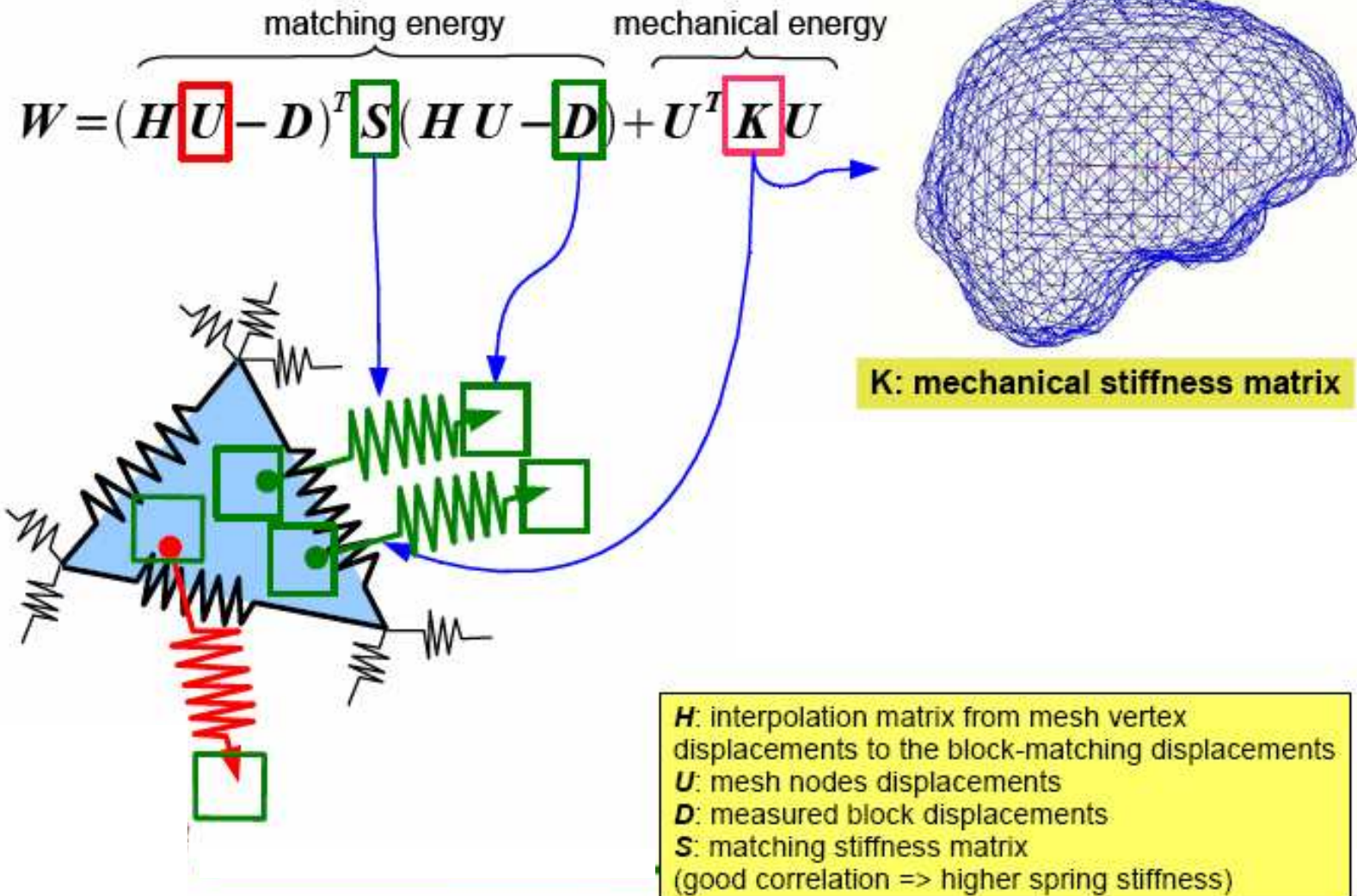
- n Local polynomial transformation (mesh based)

Polynomial Transformation

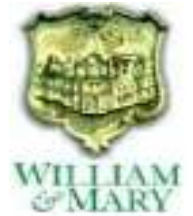


H : interpolation matrix from mesh vertex displacements to the block-matching displacements
 U : mesh nodes displacements
 D : measured block displacements
 S : matching stiffness matrix
(good correlation => higher spring stiffness)

Approximation

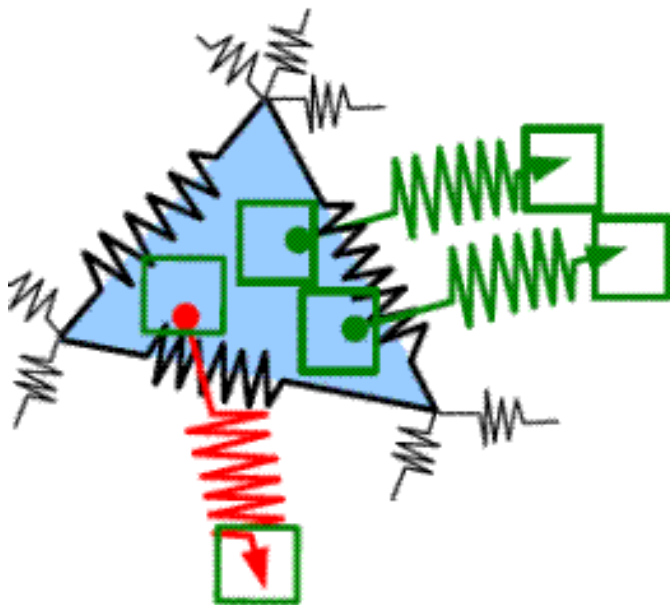


Current solution



O. Clatz et al. "Robust nonrigid registration to capture brain shift from intra-operative MRI", IEEE Trans Med Img 24(11), 2005

$$W = (H U - D)^T S (H U - D) + U^T K U$$



$$\begin{aligned} [K + H^T S H] U &= H^T S D \\ [K + H^T S H] U &= H^T S D + F \end{aligned}$$

Single iteration of outlier rejection:

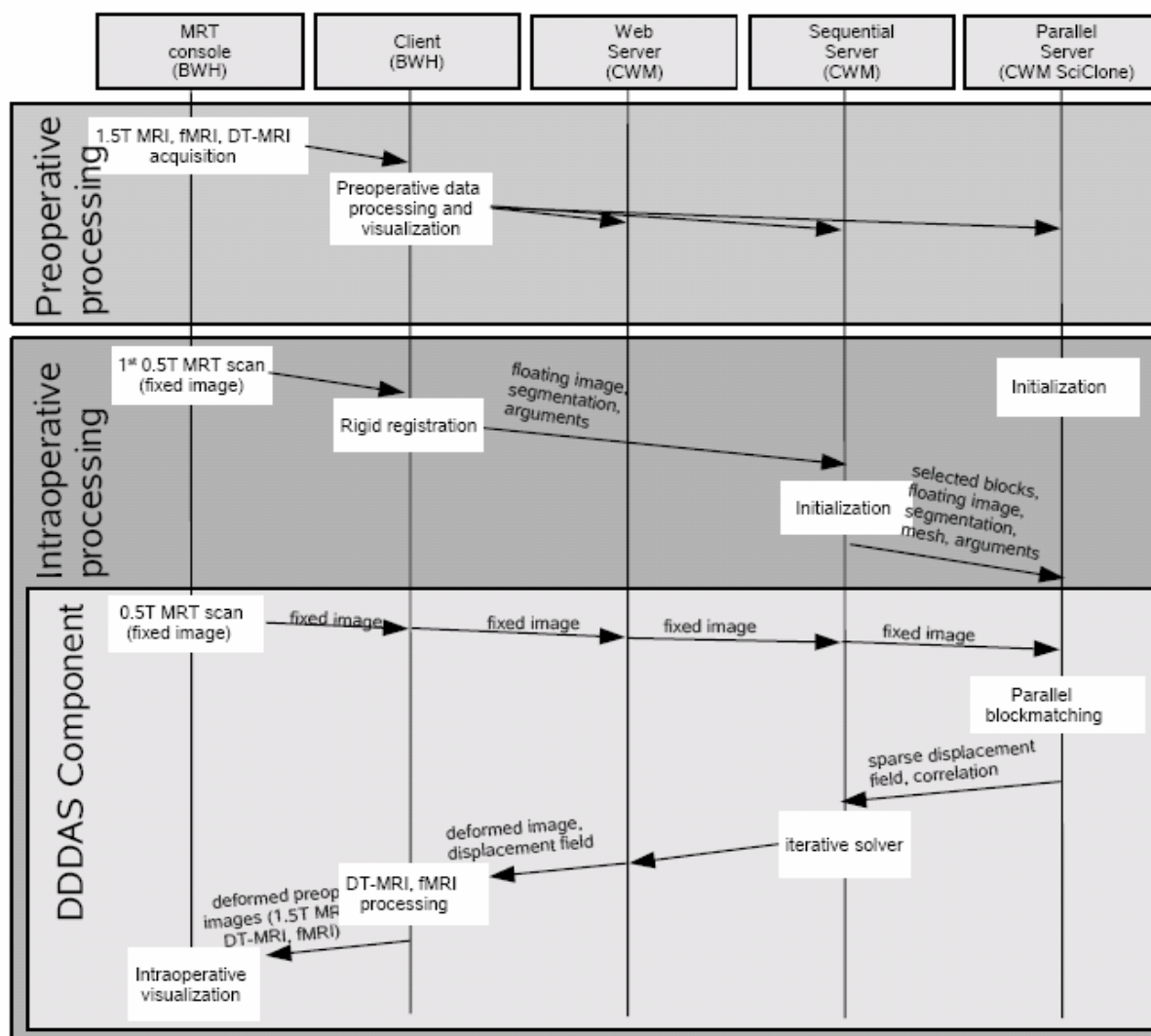
$$F_i \leftarrow K U_i$$

$$U_{i+1} \leftarrow [K + H^T S H]^{-1} [H^T S D + F_i]$$

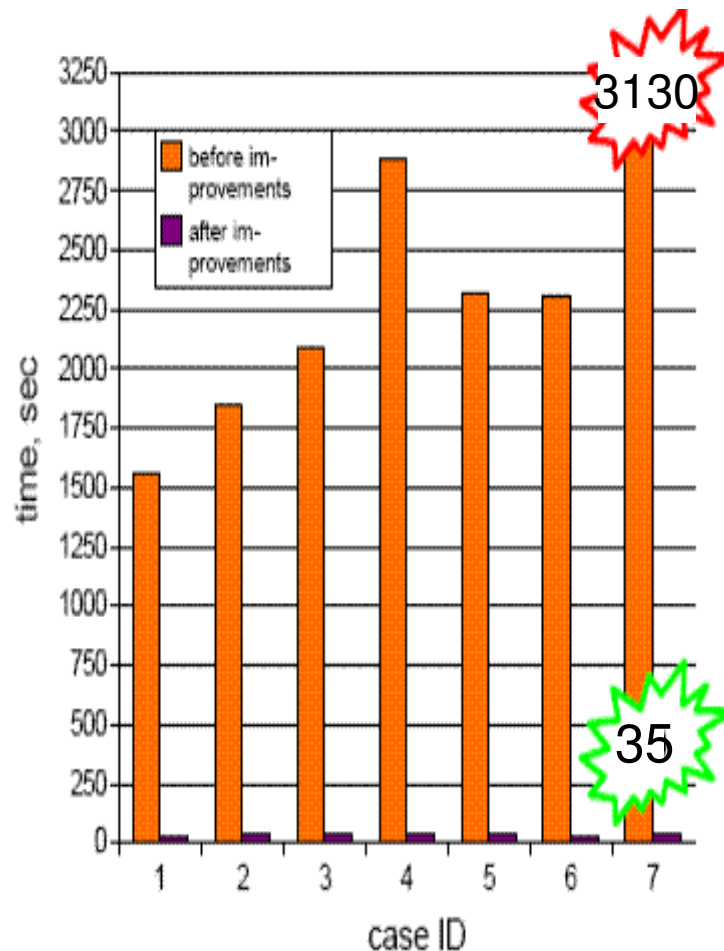
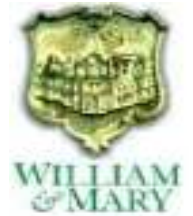
discard outliers based on $\text{diff}(H U_i - D)$

$$[H^T S H] U = H^T S D$$

Distributed & Grid Computing: Current Setting:



Near Real-time



Setup	ID						
	1	2	3	4	5	6	7
WM-HPC, using original PVM implementation on 4 PEs	1558	1850	2090	2882	2317	2302	3130
WM-SciClone (240 procs), no load-balancing (MPI)	745	639	595	617	570	550.4	1153
Pre- and post-processing on single CS node, BM on WM-SciClone (240 procs), no load-balancing	226	123	182	189	217	174	189
Pre- and post-processing on single CS node, pre-processing in advance, BM on WM-SciClone (240 procs), dynamic load-balancing	35	53	56	47	42	42	48
Pre- and post-processing on single CS node, pre-processing in advance, BM on WM-SciClone (240 procs) and WM-CSLab(29 procs), dynamic 2-level load-balancing for FT	30	40	42	37	34	33	35

(Toward) Real-Time Image Guided Neurosurgery Using Distributed and Grid Computing, (with [A. Fedorov](#), [A. Kot](#), Neculai Archip, Peter Black, Olivier Clatz, Alexandra Golby, Ron Kikinis, Simon K. Warfield), in SC06.

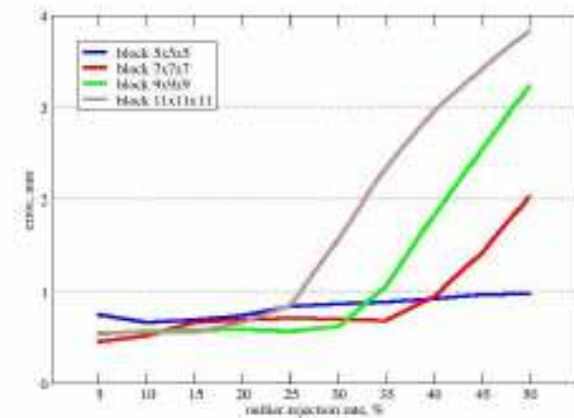
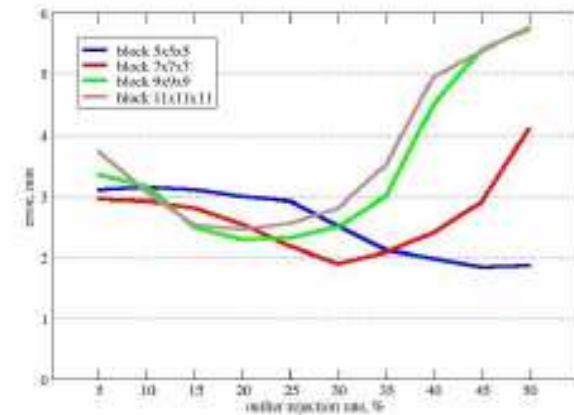
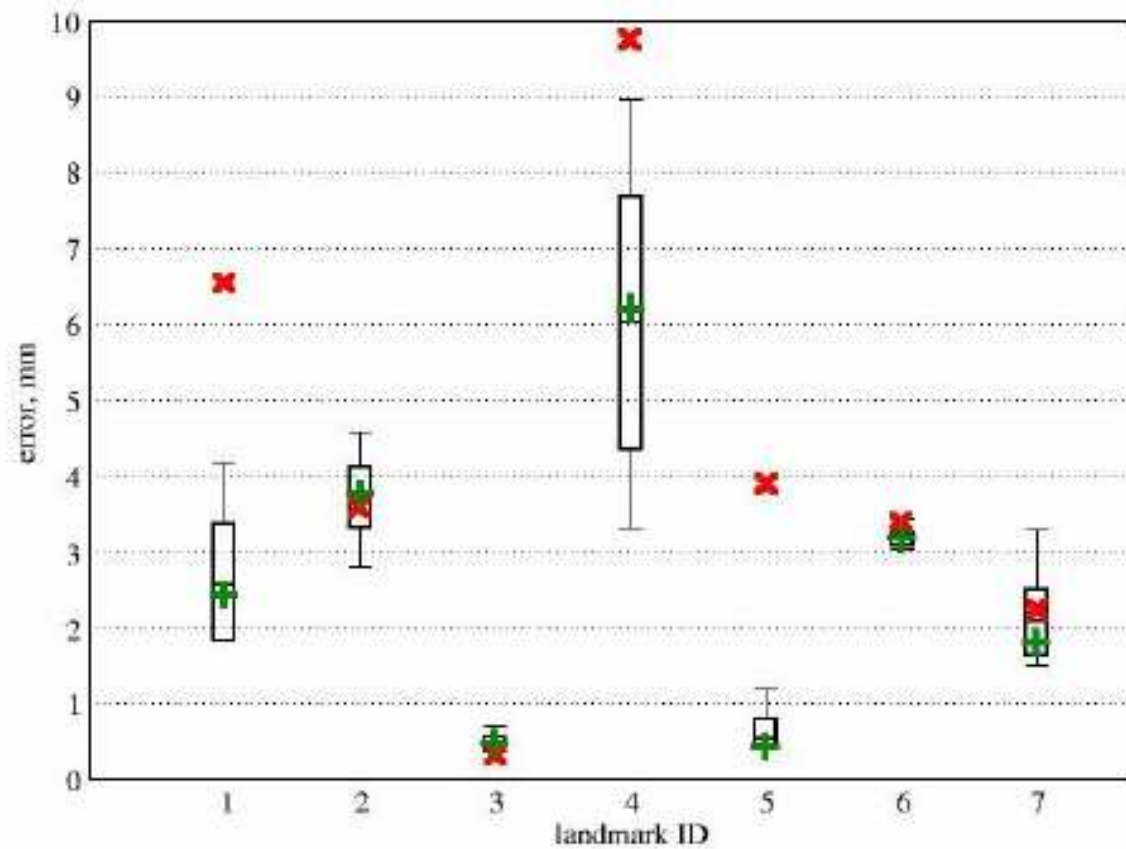
Accuracy



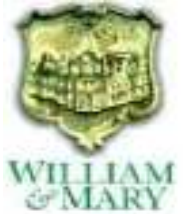
	Tumor position	Sex/ Age	Registration between preoperative and intraoperative scans (95% Hausdorff distance)			
			Max Displacement measured (mm)	Rigid - preop to intraop (mm)	Non-Rigid – preop to Intraop (mm)	Ratio Rigid/Non-Rigid
Case 1	right posterior frontal	F/29	10.68	5.95	1.90	3.13
Case 2	left posterior temporal	M/54	21.03	10.71	2.90	3.69
Case 3	left medial temporal	F/57	15.27	7.65	1.70	4.50
Case 4	left temporal	M/54	10.00	6.80	0.85	8.00
Case 5	right frontal	F/33	9.87	5.10	1.27	4.01
Case 6	left frontal	M/62	17.48	10.20	3.57	2.85
Case 7	right medial temporal	F/50	19.96	9.35	2.55	3.66
Case 8	right frontal	M/40	17.44	8.33	1.19	7.00
Case 9	right frontotemporal	M/28	15.08	7.14	1.87	3.81
Case 10	right occipital	F/56	9.48	5.95	1.44	4.13
Case 11	left frontotemporal	M/34	10.74	4.76	0.85	5.60
Table 1. Numerical accuracy results for the non-rigid registration algorithm and its comparison with conventional rigid-registration.						

Non-rigid alignment of preoperative MRI, fMRI, DT-MRI, with intra-operative MRI for enhanced visualization and navigation In image-guided neurosurgery (with N. Archip, O. Clatz, A. Fedorov, A. Kot, S. Whalen, D. Kacher, F. Jolesz, A. Golby, P. Black, S Warfield) in **NeuroImage** (in press), Feb. 2007.

Accuracy: Can we do better?

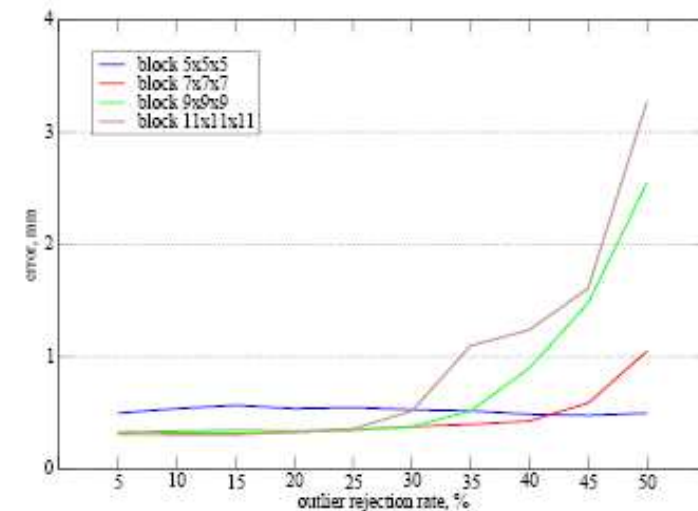
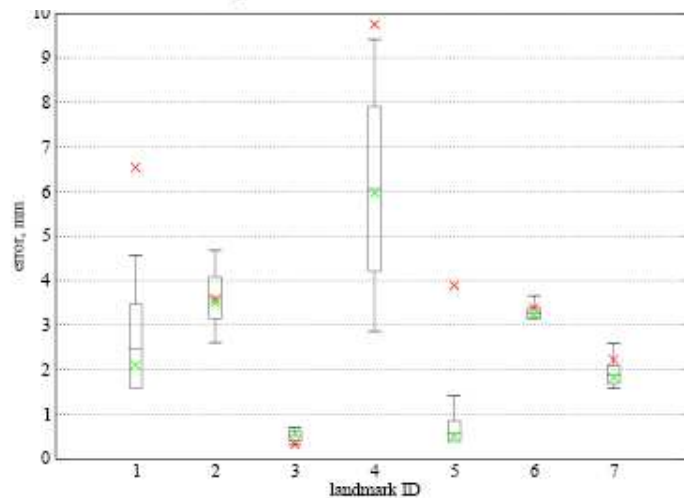


Problem: parameter search

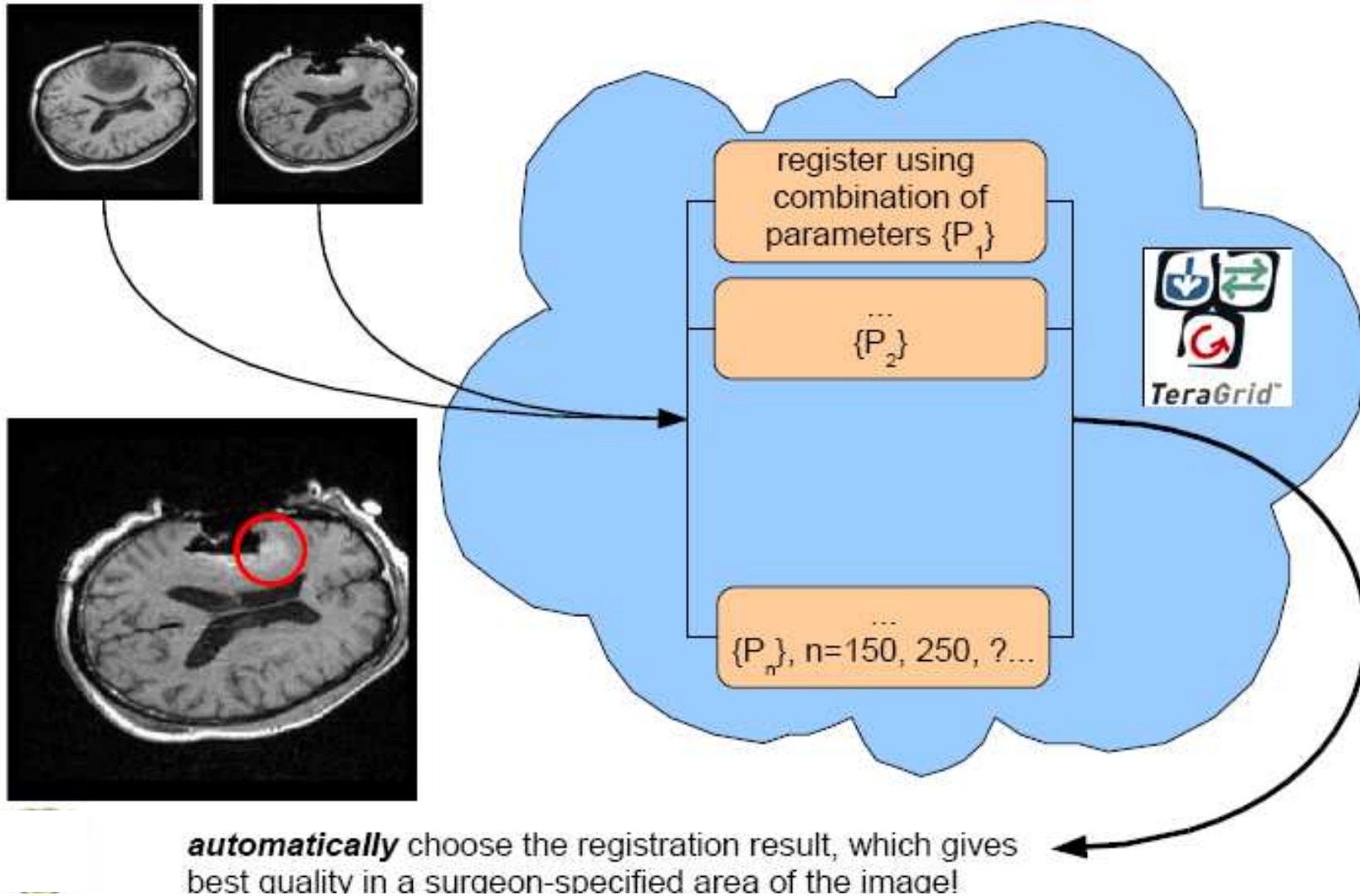


- 1: get the number of rejection steps n_R from user
- 2: get the fraction of total blocks rejected f_R from user
- 3: **for** $i = 0$ to n_R **do**
- 4: $F_i \leftarrow KU_i$
- 5: $U_{i+1} \leftarrow [K + H^T SH]^{-1} [H^T SD + F_i]$
- 6: **for all** blocks k **do**
- 7: compute error function ξ_k
- 8: **end for**
- 9: reject $\frac{f_R}{n_R}$ blocks with highest error function ξ
- 10: recompute S, H, D
- 11: **end for**
- 12: **repeat**
- 13: $F_i \leftarrow KU_i$
- 14: $U_{i+1} \leftarrow [K + H^T SH]^{-1} [H^T SD + F_i]$
- 15: **until** convergence

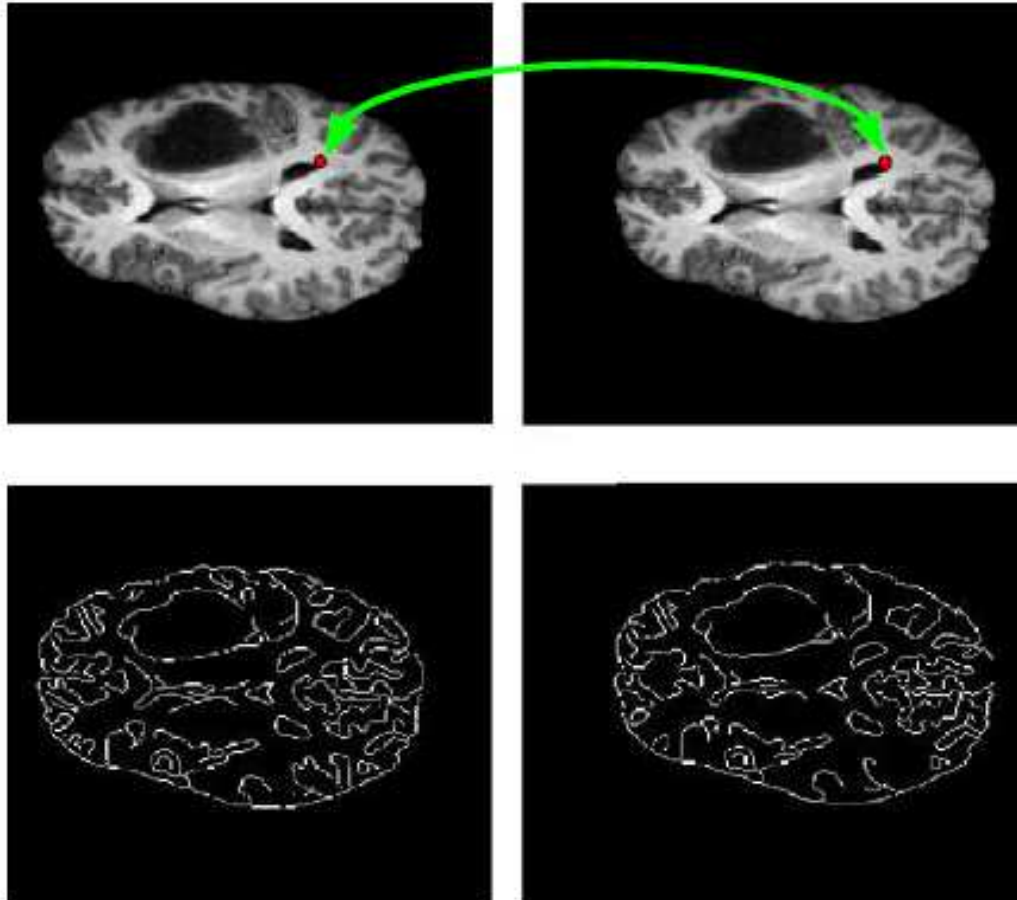
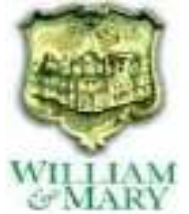
description	default setting
Young modulus (E)	694 Pa
Poisson's ratio (ν)	0.45
selected block fraction (f_B)	10%
block connectivity ($bConn$)	26
block size ($bSize$)	$7 \times 7 \times 7$
window size ($wSize$)	$11 \times 11 \times 25$
search step ($sStep$)	$1 \times 1 \times 1$
# of rejection steps (n_R)	10
rejected blocks fraction (f_R)	25%
energy trade-off (α)	$\frac{trace(K)}{n}$
error model breakup point (λ)	0.5
CG precision (r_{CG})	0.001



Intra-operative Parametric Search



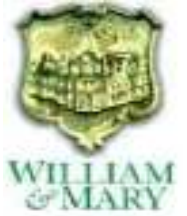
Automatic Intra-operative Validation



- current validation method:
distance between expert-
placed anatomical
landmarks: not feasible
intraoperatively

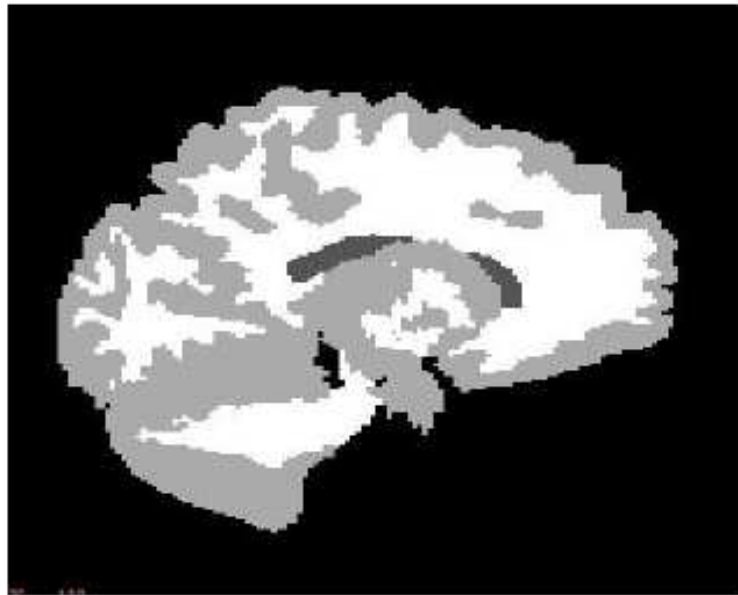
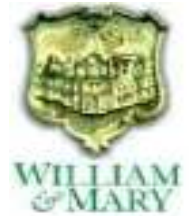
Automatically detect
image features ???

Summary



- n The method is less accurate where it is needed most, near by the tumor
 - q Better selection of outliers ?
- n Real-time search of the parametric space for the model - accuracy
 - q Grid computing – multiple registrations
 - n Intra-operative and automatic validation of results ?
 - n Can mathematical modeling be used as one of many filters for intra-operative validation of non-rigid registration results?

Future Work: multi-tissue real-time FEM mesh generation in non-rigid registration



- improve registration by more realistic deformation modeling using multiple materials
- extend the existing mesher to generate a mesh conforming to the boundary between tissues

