

Contents

1	Introduction	10
1.1	Motivation and Aims	10
1.1.1	Functional Imaging	10
1.1.2	Computational Neuroanatomy	12
1.2	Overview of Chapters	14
2	Rigid Body Registration	18
2.1	Introduction	18
2.2	Affine Transformations	19
2.2.1	Parameterising a Rigid Body Transformation	21
2.2.2	Working with Volumes of Differing or Anisotropic Voxel Sizes	22
2.2.3	Left- and Right-handed Co-ordinate Systems	22
2.3	Resampling Images	23
2.4	Optimisation	26
2.5	Within Modality Image Registration	27
2.5.1	Methods	28
2.5.2	Residual Artifacts from PET and fMRI	30
2.6	Between Modality Image Registration	31
2.6.1	Methods	32
2.6.2	Evaluation	35
3	Image Warping using Basis Functions	40
3.1	Introduction	40
3.2	Methods	42
3.2.1	<i>A Maximum A Posteriori</i> Solution	42
3.2.2	Affine Registration	45
3.2.3	Nonlinear Registration	46
3.2.4	Linear Regularisation for Nonlinear Registration	51
3.2.5	Templates and Intensity Transformations	54
3.3	Evaluation	57
3.3.1	Evaluation of the MAP Scheme for Affine Registration	57
3.3.2	Comparing Spatial Normalisation both With and Without Nonlinear Deformations	60

3.4 Discussion	62
4 High-Dimensional Image Warping	65
4.1 Introduction	65
4.2 Methods	67
4.2.1 Bayesian Framework	67
4.2.2 Likelihood Potentials	68
4.2.3 Prior Potentials - 2D	68
4.2.4 Prior Potentials - 3D	70
4.2.5 The Optimisation Algorithm	73
4.2.6 Inverting a Deformation Field	75
4.3 Examples	78
4.3.1 Two Dimensional Warping Using Simulated Data	78
4.3.2 Registering Pairs of Images	78
4.3.3 Registering to an Average	83
4.4 Discussion	91
4.4.1 Parameterising the Deformations	91
4.4.2 The Matching Criterion	92
4.4.3 The Priors	93
4.4.4 The Optimisation Algorithm	96
5 Image Segmentation	98
5.1 Introduction	98
5.2 Methods	101
5.2.1 Estimating the Cluster Parameters	102
5.2.2 Assigning Belonging Probabilities	103
5.2.3 Estimating and Applying the Modulation Function	104
5.3 Evaluation	106
5.3.1 Stability With Respect to Misregistration with the Prior Probability Images	110
5.4 Discussion	110
6 Morphometry	116
6.1 Introduction	116
6.1.1 Multivariate Analysis of Covariance	118
6.1.2 Canonical Correlation Analysis	119
6.2 Voxel-Based Morphometry	120
6.2.1 Methods	121
6.2.2 Evaluations	122
6.3 Deformation Based Morphometry	127
6.3.1 Methods	128
6.3.2 Results	131
6.4 Tensor-Based Morphometry	132
6.4.1 Theory	135

6.4.2	Data for Evaluations	138
6.4.3	Morphometry on Jacobian Determinants	139
6.4.4	Morphometry on Strain Tensors	144
6.5	Discussion	146
7	Discussion	151
7.1	Original Contributions	151
7.2	Modularity	152
7.3	Hyper-parameter estimation	153
References		157

List of Figures

1.1	Deformation- and tensor-based morphometry.	13
2.1	Left- and right-handed co-ordinate systems.	23
2.2	Image interpolation in two dimensions.	24
2.3	Sinc function in two dimensions.	25
2.4	The optimisation can be thought of as fitting a series of quadratics.	28
2.5	Example of registered PET and MRI.	36
2.6	Example of registered T1 and T2 weighted images.	37
3.1	Illustration of Bayes rule.	43
3.2	Different boundary conditions.	48
3.3	Discrete Cosine Transform basis functions.	49
3.4	Deformation fields consist of a linear combination of basis functions.	50
3.5	The fast algorithm.	50
3.6	Example template images.	55
3.7	Two dimensional histograms of template images.	55
3.8	Simulated images of T1, T2 and PD weighted images.	56
3.9	Average χ^2 for the images plotted against iteration number.	59
3.10	Number of iterations in which convergence to within 1% is reached.	59
3.11	Parameter estimates from reduced data versus those from complete data.	60
3.12	Means and standard deviations of spatially normalised images.	61
3.13	Illustration of the effect of regularisation.	63
4.1	Triangular mesh used for 2D registration.	69
4.2	Probability density functions.	71
4.3	Tetrahedral mesh used for 3D registration.	72
4.4	A comparison of the different cost functions.	74
4.5	The six triangles whos Jacobian matrices are influenced by the central point.	75
4.6	C code for computing the rate of change of the prior potential.	76
4.7	An illustration of how voxels are located within a tetrahedron.	77
4.8	Demonstration using simulated data.	79
4.9	Demonstration of the reversibility of the deformations.	80
4.10	Example of 2D registration of brain images.	81
4.11	Example of 3D registration of brain images.	82

4.12 Deformation fields from 3D registration.	83
4.13 Symmetry of 3D deformation fields.	84
4.14 Mean and standard deviation images.	85
4.15 Affine registered images.	86
4.16 Basis function registered images.	87
4.17 High-dimensionally registered images.	88
4.18 Rendered brain surfaces showing equivalent locations.	89
4.19 Mappings obtained by combining warps.	90
4.20 A comparison of a symmetric with an asymmetric likelihood potential.	94
4.21 Rotation and translations of a region, keeping surrounding points stationary.	95
4.22 A shear has singular values not equal to one.	95
5.1 Prior probability images.	99
5.2 The segmentation model.	100
5.3 A flow diagram for the tissue classification.	102
5.4 Algorithm for computing $\mathbf{A}_k^T \mathbf{A}_k$ and $\mathbf{A}_k^T \mathbf{b}_k$ in two dimensions.	105
5.5 Randomly generated modulation fields.	106
5.6 Example segmentation of real data.	107
5.7 Classification of the simulated BrainWeb image.	108
5.8 Recovery of modulation field.	111
5.9 Segmentation accuracy with respect to misregistration.	112
5.10 Effects of partial volume on the intensity histograms.	113
5.11 Example of automatically cleaned up segmented images.	115
6.1 Canonical correlation analysis using simulated data.	120
6.2 Histogram of correlation coefficients.	124
6.3 Histograms of t-scores from randomly generated tests.	126
6.4 Frequency of false positives.	127
6.5 Template and weighting images.	129
6.6 Means of spatially normalised images for each group.	129
6.7 Separation of subjects using canonical correlation analysis.	132
6.8 Caricatured shape differences.	133
6.9 Average shape differences.	134
6.10 Warping of same subject brain during Alzheimers disease progression.	136
6.11 Volume changes during progression of Alzheimers disease.	137
6.12 Polar decomposition.	137
6.13 Mean of 58 warped hippocampus images.	139
6.14 Randomly chosen warped images of hippocampi.	140
6.15 Jacobian determinant fields.	142
6.16 Histogram of correlation coefficients.	143
6.17 Histograms of t-scores from randomly generated tests.	143
6.18 More histograms of t-scores from randomly generated tests.	145

6.19 Histogram of Q-Q plot correlation coefficients taken over tensor fields.	146
6.20 Histograms of Wilk's Λ statistics.	147

List of Tables

2.1	Errors for PET-MRI registration	38
2.2	Errors for PET-MRI registration from other methods.	38
5.1	κ statistics computed from classified simulated images.	111