

Table of Contents

List of Figures	<i>xiii</i>
List of Tables	<i>xv</i>
List of Abbreviations	<i>xvii</i>
Perface	<i>xix</i>

Part – I BACKGROUND

Chapter 1

Introduction: Image Registration & Deformable Image Registration.....	3
1.1 Brief Overview of Image Registration	3
1.2 Outline of Medical Image Registration	5
1.3 Notes on Deformable Image Registration	7
1.4 Problems with Deformable Registration of Abdominal Images	9
1.5 Thesis Objectives.....	10
1.6 Thesis Contribution	10
1.7 Thesis Organization	10
References	12

Chapter 2

Deformable Registration with Traditional Method.....	15
2.1 Similarity Measures	16
2.2 Transformations	17
2.2.1 Parametric Transformation Functions.....	17
2.2.2 Non-parametric Transformation Functions.....	19
2.3 Optimization Methods	19
2.3.1 Hierarchical Approaches	20
2.3.2 Methods for Parametric Registration.....	20
2.3.3 Methods for Non-parametric Registration.....	21
2.4 Notable Works	23
References	26

Chapter 3

Deformable Registration with Deep Neural Networks.....	31
3.1 Supervised Transformation Estimation	32
3.1.1 Fully Supervised Transformation Estimation.....	33

3.1.2 Dual/Weakly Supervised Transformation Estimation	34
3.2 Unsupervised Transformation Estimation	32
3.2.1 Similarity Metric-based Unsupervised Transformation Estimation	36
3.2.2 Feature-based Unsupervised Transformation Estimation	37
References	39

**Part – II USING CONVENTIONAL APPROACH
FOR DEFORMABLE REGISTRATION**

Chapter 4

Non-Rigid Registration of Multimodal Images

(Ultrasound And CT) of Liver Using Gradient Orientation Information	45
Abstract.....	45
4.1 Introduction	46
4.2 Methodology.....	48
4.2.1 Overview of the Algorithm	48
4.2.2 Liver Surface Features.....	49
4.2.3 Segmentation (Mask Generation)	50
4.2.4 Calculation of Edge Orientation	52
4.2.5 Best Matched Slice Selection.....	53
4.2.6 Calculation of Objective Function	53
4.2.7 Transformation Estimation for Registration	54
4.3 Experimentation	56
4.3.1 Data Acquisition.....	56
4.3.2 Experimental Results	56
4.4 Conclusion.....	57
References	57

Chapter 5

Non-Rigid Registration (Computed Tomography – Ultrasound)

of Liver Using B-Splines and Free Form Deformation.....	59
Abstract.....	59
5.1 Introduction	60
5.1.1 Background	61
5.1.2 Related Work	62
5.2 Methodology (Image Registration)	64
5.2.1 Preprocessing	65

5.2.2 Global Motion Model	65
5.2.3 Local Motion Model	65
5.2.4 Similarity Measure	67
5.2.5 Deformation Regularization	67
5.2.6 Optimization	68
5.3 Registration Refinement	68
5.3.1 Using Multi-level B-splines	69
5.3.2 Using Gradient Orientation Information	71
5.3.2.1 Segmentation (Mask Generation)	71
5.3.2.2 Entropy Based Objective Function	71
5.3.2.3 Transformation Estimation	73
5.4 Optimization	73
5.4.1 Steepest Gradient Descent Method	73
5.4.2 Quasi-Newton Method	73
5.4.3 Levenberg-Marquardt Method	75
5.5 Experimentation	76
5.5.1 Data Acquisition	76
5.5.2 Experimental Results	77
5.5.2.1 Accuracy	78
5.5.2.2 Precision (of Optimization Techniques)	79
5.5.2.3 Discussion	81
5.5.2.4 Limitations	82
5.6 Conclusion	83
References	83

**Part – III USING LEARNING-BASED APPROACH
FOR DEFORMABLE REGISTRATION**

Chapter 6

Evaluation of A Learning Based

Deformable Registration Method on Abdominal CT Images	89
Abstract	89
6.1 Introduction	90
6.2 Material and Methods	92
6.2.1 Datasets	92

6.2.2 Background on Image Registration	92
6.2.3 CNN-based Registration: VoxelMorph	94
6.2.4 CNN Architecture	95
6.2.5 Cost Function	96
6.2.6 Spatial Transformer Function	97
6.3 Experiments and Results	98
6.3.1 Experimental Setup.....	98
6.3.1.1 Dataset Preperation	99
6.3.1.2 Evaluation Metric	101
6.3.1.3 Comparison with a State-of-the-Art Method.....	103
6.3.2 2D Atlas-based Registration	104
6.3.3 2D Pairwise Registration	106
6.3.4 3D Pairwise Registration	109
6.3.5 Setting of the Regularization Parameter	111
6.4 Discussion.....	112
6.4 Conclusion.....	116
References	117

Part – IV CLOSURE

Chapter 7

Summary and Conclusion	121
------------------------------	-----

Chapter 8

Future Scope of Work	123
References	124

Part – V ACCOMPLISHMENTS

Publications (Journal Articles)	127
Publications (Conference Articles).....	127
Achievements	127
Conferences and Workshops.....	128
Other Publications (During Doctoral Studies)	128
Permission form Ethical Committee	129

LIST OF FIGURES

Figure No.	Figure description	Page No.
Figure 4.1	Block diagram of proposed algorithm	48
Figure 4.2	Gradient orientation of liver surface (a), (b), (c) US image, (d), (e), (f) contrast enhanced CT image	50
Figure 4.3	Mask Generation liver surface: (a), (b), (c) US image, (d), (e), (f) CT image	51
Figure 4.4	Registration: (a),(b) US image, (c),(d), selected CT image, (e),(f) US-CT registered	55
Figure 5.1	Block diagram of image registration	64
Figure 5.2	Configuration of multi-resolution control point grid; Refinement of grid with deformation (left); Calculation of grid subdivision (right)	70
Figure 5.3	US image (leftmost); US image with masking (second from left); Enhanced CT image (third from left); Enhanced CT image with masking (rightmost); Image reproduced from [2]	70
Figure 5.4	Graphical representation of Distance Measurement values (in mm) for clinical datasets	79
Figure 5.5	Registration results (Algo-1 & Algo-2, Third & Fourth rows) using SGD (Left); QSN (Middle) and LVM (Right)	80
Figure 6.1	Left side: Block diagram illustrating the VoxelMorph method Right side: UNet Architecture considered for VoxelMorph CNN Channel number and image spatial resolution are written inside and under the boxes, respectively	95
Figure 6.2	(a) original 2D abdominal image; (b) 2D abdominal image after bed removal; (c) original 2D abdominal image and (d), (e), (f) examples of warped images generated with Gryds package for data augmentation	99
Figure 6.3	Example of 2D atlas-based registration. For images in first row: Dice Score (affine registration) 0.852; Dice Score (VoxelMorph) 0.94; Hausdorff Distance (affine registration) 5.291; Hausdorff Distance (VoxelMorph) 4.690 For images in second row: Dice Score (affine registration) 0.8812; Dice Score (VoxelMorph) 0.9355; Hausdorff Distance (affine registration) 4.472; Hausdorff Distance (VoxelMorph) 4.243	105

Figure 6.4	Example of 2D Pairwise Registration For images in first row: Dice Score (affine registration) 0.7962; Dice Score (VoxelMorph) 0.9019; Hausdorff Distance (affine registration) 3.873; Hausdorff Distance (VoxelMorph) 3.742; For images in second row: Dice Score (affine registration) 0.8967; Dice Score (VoxelMorph) 0.9406; Hausdorff Distance (affine registration) 4.795; Hausdorff Distance (VoxelMorph) 4.013	105
Figure 6.5	Dice Scores: Mean (\pm SD); 3D-IRCADb-01; model trained using (left) MSE, (right) CC	108
Figure 6.5	Hausdorff Distance: Mean (\pm SD); 3D-IRCADb-01; trained using (left) MSE,(right) CC	108
Figure 6.7	Example of 3D Pairwise Registration (using MSE); Dice Score (affine registration) 0.7093; Dice Score (VoxelMorph) 0.7955 Hausdorff Distance (affine registration) 27.9464; Hausdorff Distance (VoxelMorph) 21.7715	108
Figure 6.8	LiTS volume registration with segmentation overlapping; Triplanar view and 3D view 1st row:If; 2nd row: Im; 3rd row: Im \circ (using VoxelMorph); 4th row: Im \circ (using ANTS(SyN)) for Affine: Dice Score: 0.7941 ; Hausdorff Distance: 20.832 for VoxelMorph: Dice Score: 0.881 ; Hausdorff Distance: 19.261 for ANTS(Syn): Dice Score: 0.8981 ; Hausdorff Distance: 18.973	110
Figure 6.9	3D-IRCADb-01 vol. registration with segmentation overlapping; Triplanar & 3D view; 1st row:If; 2nd row: Im; 3rd row: Im \circ (using VoxelMorph); 4th row: Im \circ (using ANTS(SyN)) for Affine: Dice Score: 0.8084 ; Hausdorff Distance: 21.071 for VoxelMorph: Dice Score: 0.9079 ; Hausdorff Distance: 15.394 for ANTS(Syn): Dice Score: 0.9126 ; Hausdorff Distance: 14.817	111
Figure 6.10	Influence of the regularisation weighting parameter, for 2D Atlas-based Registration	112
Figure 6.11	Example of 2D Atlas-based Registration (poor case for VoxelMorph) Dice Score (affine registration) 0.78699; Dice Score (VoxelMorph) 0.8949; Hausdorff Distance (affine registration) 5.099; Hausdorff Distance (VoxelMorph) 4.472	113
Figure 6.12	Example of 2D Pairwise Registration (poor case for VoxelMorph) Dice Score (affine registration) 0.83547; Dice Score (VoxelMorph) 0.8932; Hausdorff Distance (affine registration) 6.557; Hausdorff Distance (VoxelMorph) 5.477	113

LIST OF TABLES

Table No.	Table description	Page No.
Table 2.1	Exploration of related useful literatures	24
Table 3.1	Exploration of related literatures (supervised deformable transformation estimation)	35
Table 3.2	Exploration of related literatures (supervised deformable transformation estimation)	38
Table 4.1	Performance evaluation of proposed algorithm	57
Table 5.1	Registration accuracy test values (Distance Measurement (in mm): Mean (\pm SD))	78
Table 5.2	Precision test results of optimization techniques	79
Table 6.1	Quantitative Results (2D atlas-based abdominal image registration)	107
Table 6.2	Quantitative Results (2D pairwise abdominal image registration)	107
Table 6.3	Quantitative Results (3D pairwise abdominal image registration; model using MSE)	107
Table 6.4	Quantitative Results (3D pairwise abdominal image registration; model using CC)	107

LIST OF ABBREVIATIONS

MRI	Magnetic Resonance Imaging
US	Ultrasound
CT	Computed Tomography
PET	Positron Emission Tomography
SPECT	Single-Photon Emission Computed Tomography
fMRI	Functional Magnetic Resonance Imaging
TRUS	Transrectal Ultrasound
HIFU	High Intensity Focused Ultrasound
DIR	Radiofrequency Ablation
RFA	Deformable Image Registration
SSD	Sum Of Squared Differences
CC	Cross Correlation
NCC	Normalized Cross Correlation
MI	Mutual Information
NMI	Normalised Mutual Information
MSE	Mean Squared Error
MSD	Mean Squared Difference
SSIM	Structural Similarity Index Measure
RBF	Radial Basis Function
TPS	Thin Plate Spline
EBS	Elastic Body Spline
GEBS	Gaussian Elastic Body Spline
FFD	Free Form Deformation
GD	Gradient Descent
CG	Conjugate Gradient
SGD	Steepest Gradient Descent
QSN	Quasi-Newton

DFP	Davidon-Fletcher-Powell
LVM	Levenberg – Marquardt
HAMMER	Hierarchical Attribute Matching Mechanism for Elastic Registration
LDDMM	Large Deformation Diffeomorphic Metric Mapping
BFGS	Broyden - Fletcher - Goldfarb - Shanno
L-BFGS	Limited Memory Broyden - Fletcher - Goldfarb - Shanno
PDE	Partial Differential Equation
FCN	Fully Convolutional Network
CNN	Convolutional Neural Network
STN	Spatial Transformer Network
TRE	Target to Registration Error
ICP	Iterative Closest Point
ROI	Region of Interest
ANTs	Advanced Normalization Tools
SyN	Symmetric Normalization
CPU	Central Processing Unit
GPU	Graphics Processing Unit