Novel index for image quality and its application to evaluate quality of compressed and de-noised images based on sparse

Sheikh Md. Rabiul Islam
Student ID: u3079213

A Thesis Submitted for the Degree of Doctor of Philosophy (Information Sciences and Engineering (235AA)) of the University of Canberra, Australia.

February 2015

Faculty of Education, Science, Technology & Mathematics

UNIVERSITY OF CANBERRA

AUSTRALIA'S CAPITAL UNIVERSITY

Dedication

To my wife Sadia Afroj and son Rafnan Islam for their love and patience.

Abstract

Indexes used for evaluation of image quality (EIQ) are provided with computational models to measure the quality of images in a perceptually consistent manner. Electronic industries are continuously moving forward with new products and technologies for digital cameras introduced in the market. Therefore it is necessary to have improved methods to verify that these technological advancements lead to higher quality images. This thesis reports the invention of a novel index for evaluation of image quality and its application for image compression and de-noising. The intended behavior of such metrics is to measure image quality as human observers would perceive it.

The thesis first gives a background for image quality assessment, including the concept of image quality indexes. It was recognized that human vision was very sensitive to the distribution of brightness in an image; so here is an additional factor denoting, the shape of brightness histogram which is the difference between the grey-level histograms of the original and the distorted image into Structural Similarity Index Measure (SSIM). The proposed index, therefore, becomes a combination of four factors: luminance, contrast, structure and shape of brightness histogram. To ensure that the index can assist human observations in image quality evaluation, it needs to be assessed. A new method based on the ranking order was developed to assess the overall performance of image quality metrics. The proposed image quality index was assessed using existing traditional methods based on a set of public databases, which contains digital images of a range of different distortions, quality issues and quality ratings from human observers.

The thesis then continues with some applications of the proposed image quality index in image compression and de-noising. It extends the commonly used algorithms for image compression and compares their performance. For image compression techniques, it has linked different wavelet techniques such as traditional mother wavelets and lifting based on Cohen-Daubechies-Feauveau wavelets with the low-pass filters of the length 9 and 7 (CDF 9/7), wavelet transform with Set Partition in Hierarchical Trees (SPIHT) algorithm and entropy coding. The main key point is to be demonstrated on the basis of proposed image quality index; the choice of mother wavelet becomes very important to achieve superior wavelet compression performances. An image de-noising, proposes a new de-noising algorithm based on Cohen-Daubechies-Feauveau (CDF 9/7) wavelet transforms. The results of proposed compression

schemes show approximately 99% compression ratio and approximately 1 value of EIQ. It also proposes a new image de-noising approach using an optimum adaptive shrinkage threshold obtained with a proportional, integral and derivative (PID) tuning algorithm in the shearlet domain. The proposed de-noising algorithm is more efficient for images contaminated with popular noises such as Gaussian noise, Poisson noise and impulse (salt $\&$ pepper) noise than all other methods. Experimental results show that images de-noised with the proposed approach have higher qualities than those produced with some of other de-noising methods like wavelet-based, bandlet-based, and curvelet-based using novel image quality indexes. The de-noised image is justified by EIQ and it's approximately 1.

The thesis also reports new algorithms, based on sparse, for image compression and de-noising. Compressed sensing (CS) is a new sampling theory that has recently been introduced for efficient acquisition of compressible signals. Compressed sensing (CS) states that if signals are sparse in some bases, then they will be recovered from a small number of random linear measurements via attractable convex optimization techniques. In this part of the thesis, these are two main contributions. In the first contribution, it is compressed images: high data throughput is becoming increasingly important in image, with high-resolution cameras (i.e., large numbers of samples per acquisition) and long observation times. The compressed sensing theory provides a framework to reconstruct images from fewer samples than traditional acquisition approaches. However, the very few measurements must be spread over a large field of view, which is difficult to achieve in conventional cameras. In this sense, it is proposes a novel method for compressive sensing of image reconstruction based on sparse representation of lifting scheme based on CDF 9/7 wavelet transform which is computational scheme to perform fast temporal acquisitions. In the second contribution, image de-noising: digital cameras images suffer from complex artifacts associated with low dark noise conditions. It has also proposed a novel image de-noising algorithm based on compressive sensing using multiple random under sampling in the sparse CDF9/7 wavelet domain and the Total Variation de-noising algorithm and adaptive Texture Variation with Adaptive Fidelity (ATVD) de-noising algorithm as a spatial sparsity prior for digital imaging. The experimental results of proposed image compression or de-noising method based on CS frameworks provide higher quality compressed and de-noised images compared the methods on open sources databases.

Acknowledgements

There are many people who deserve to be acknowledged; without their support and help it would not have been possible to complete this thesis. First, I would like to thank my Ph.D. program supervisor **Professor Dr. Xu Huang**, Academic Program of Information Technology and Engineering, Faculty of Education, Science, Technology & Mathematics, University of Canberra, Australia. His understanding, encouraging, supporting and guiding have made the present thesis possible. I am deeply grateful to my co-supervisor, **Dr. Kim Le**, assistant professor of Academic Program of Information Technology and Engineering, Faculty of Education, Science, Technology & Mathematics, University of Canberra, Australia. I would like to thank his involvement in the work, valuable comments, suggestions, and support of my thesis as well as other publication of articles.

Many of the employees at the University of Canberra have contributed to my thesis during the last years, and in particularly, I would like to thank Jason Weber, IT Manager of technical for support. Many thanks to Serena Chong, Faculty Manger who gave me the pleasant research environment. Thanks to my research colleagues for their support and discussions.

My deepest appreciation is due to my family and friends; their support is invaluable.

Thank you all.

Sheikh Md. Rabiul Islam

February 2015

University of Canberra, Australia.

Publications Associated with the Thesis

These are the publications associated with this thesis, which have been produced by, or in conjunction with the author during his Ph.D. candidacy:

Book Chapter

1. **Sheikh Md. Rabiul Islam**, Xu Huang, and Kim Le. *A Novel Adaptive Shrinkage Threshold on Shearlet Transform for Image Denoising.* In Chu Kiong Loo, Keem Siah Yap, Kok Wai Wong, Andrew Teoh Beng Jin, and Kaizhu Huang, editors, Neural Information Processing, Volume 8836 of Lecture Notes in Computer Science, pages 127 - 134, Springer International Publishing, Switzerland 2014. Online ISBN: 978-3-319-12643-2, Print ISBN :978-3-319-12642-5.

2. **Sheikh Md. Rabiul Islam**, Xu Huang, and Kim Le. *A Novel Image Quality Index for Image Quality Assessment.* In Minho Lee, Akira Hirose, Zeng-Guang Hou, and RheeMan Kil, editors, Neural Information Processing, number 8228 in Lecture Notes in Computer Science, pages 549 - 556. Springer Berlin Heidelberg, 2013. Print ISBN : 978-3-642-42050-4, Online ISBN : 978-3-642-42051-1.

Journal Proceedings

1. **Sheikh Md. Rabiul Islam**, Xu Huang, and Keng Liang Ou. *Image Compression Based on Compressive Sensing Using Wavelet Lifting Scheme.* The International Journal of Multimedia & Its Applications(IJMA),Volume 7, Number 1, pp 1-16, February, 2015. ISSN:0975-5578 (Online); 0975-5934(print).

2. Raul Fernandez Rojas, Xu Huang1, Keng Liang Ou, Dat Tran and **Sheikh Md. Rabiul Islam**. *Analysis of Pain Hemodynamic Response Using Near-Infrared Spectroscopy (NIRS).* The International Journal of Multimedia & Its Applications(IJMA),Volume 7, Number 2, pp 31-42, April, 2015. ISSN:0975-5578 (Online); 0975-5934(print).

3. **Sheikh Md. Rabiul Islam**, Xu Huang, Kim Le. *MR Image Compression Based on Selection of Mother Wavelet and Lifting Based Wavelet.* The International Journal of Multimedia & Its Applications(IJMA),Volume 6, Number 2, pp 59-76, April, 2014. ISSN:0975-5578 (Online); 0975-5934(print).

4. **Sheikh Md. Rabiul Islam**, Xu Huang, Kim Le and Mingyu Liao. *Enhancing Quality of MR Image Based on Wavelet Algorithm.* International Journal of Computational Intelligence Research (IJCIR),Vol.9 No.1, pp. 37-53, August, 2013. Print ISSN: 0973-1873, Online ISSN: 0974-1259.

5. **Sheikh Md. Rabiul Islam**, Xu Huang, Mingyu Liao, N. K. Srinath. *Image Denoising Based on Wavelet for IR Images Corrupted by Gaussian, Poisson & Impulse Noises.* IJCSNS International Journal of Computer Science and Network Security. Vol. 13, No.6, pp. 59-70, June, 2013. ISSN: 1738-7906.

6. Mingyu Liao, Xu Huang, Dharmendra Sharma ,**Sheikh Md. Rabiul Islam**. *A New Method for Recognition and De-noising for Middle Wave Infared Imaging.* Journal of Flow Visualization and Image Processing Volume 19, Issue 2 pages 179-193, 2012. ISSN Print: 1065-3090 ,ISSN Online: 1940-4336.

7. **Sheikh Md. Rabiul Islam**, Xu Huang, and Mingyu Liao. *Compression of IR Image Based on Wavelet Algorithm.* IJCSNS International Journal of Computer Science and Network Security. Vol.12, No.12, Pages 77-84, December, 2012. ISSN: 1738-7906.

International Conferences Proceedings

1. **Sheikh Md. Rabiul Islam**, Xu Huang, and Kim Le. *Novel Evaluation Index for Image Quality.* The International Conference on Digital Image Computing: Techniques and Applications (DICTA) ,pp. 1-8, 25-27 November, 2014. ISBN: 978-1-4799-5409-4.

2. Xu Huang, **Sheikh Md. Rabiul Islam**, Mingyu Liao, and Shutao Li. *High Quality Infrared Images with Novel Algorithm for Multi-Noises Removal*. Proceedings of the World Congress on Engineering 2013 Vol III, WCE 2013, July 3 - 5, 2013. ISBN: 978-988-19252-9-9 ,ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online).

3. Xu Huang, **Sheikh Md. Rabiul Islam**, M. Liao, and Shutao Li. *Higher quality of infrared images for future network security systems.* 16th International Symposium on Wireless Personal Multimedia Communications (WPMC), pp. 16, 24-27 June, 2013. ISSN :1347-6890.

4. **Sheikh Md. Rabiul Islam**, Xu Huang, and Dharmendra Sharma. *Wavelet based denoising algorithm of the ECG signal corrupted by WGN and Poisson noise*. in 2012 International Symposium on Communications and Information Technologies (ISCIT), pp. 165168, 2-5 October, 2012. E-ISBN :978-1-4673-1155-7, Print ISBN: 978-1-4673-1156-4.

Abbreviations

AWGN	Additive White Gaussian Noise
ATVD	Total Variation with Adaptive Fidelity
BP	Basis Persuit
bior	Biorthogonal
CDF9/7	Cohen-Daubechies-Feauvean 9/7
CR	Compression Ratio
Coif	Coiflet
CSF	Contrust Sensitive Function
DWT	Discrete Wavelet Transform
DCT	Discrete Cosine Transform
DMOS	Difference Mean Opinion Score
Db	Daubechies
dB	Decibel
EIQ	Evaluation of Image Quality
FR	Full Reference
HVS	Human Vision System
HQI	Histogram Quality Index
IQA	Image Quality Assessment
IR	Infared
KROCC	Kendall Rank Order Correlation Coefficients
MAE	Mean Absolute Error
MOS	Mean Opinion Score
MR	Magnetic Resonance
MICT	Toyama Image Quality
OMP	Orthogonal Matching Pursuit
PSNR	Peak Signal-to-Noise Ratio
PDFT	Pseudo-Polar Discrete Fourier Transform
PLCC	Pearson Linear Correlation Coefficients
RMSE	Root Mean Square Error
PID	Proportional Integral and Derivative
RIP	Restricted Isometric Property
rbio	Reverse Biorthogonal
RR	Reduced Reference
SSIM	Structural Similarity Index Measure
SROCC	Spearman Rank Order Correlation Coefficients
SPIHT	Set Partition in Hierarchical Trees
Sym	Symlet
ST	Shearlet Transform
TVD	Total Variation De-noising
TID	Tampere Image Quality Database
UIQI	Universal Image Quality Index
VQEG	Video Quality Experts Group
VSNR	Visual Signal-to-Noise Ratio
WT	Wavelet Transform
WIQ	Wireless Image Quality

Contents

Abstract iii

Certificate of Authorship of Thesis v

Acknowledgements vii

Publications Associated with the Thesis ix

Abbreviations xi

List of Figures xvii

List of Tables xxiii

1 Introduction 1

1.1 Research Background 1

1.2 Problem Statements 2

1.3 Research Aims and Objectives 2

1.4 Research Methodology and Scope 2

1.5 Organization of the thesis 4

2 Literature Review 5

2.1 Image Quality Assessment 6

2.2 Evaluation of Image Quality Indexes 10

2.2.1 Image Compression Methods 10

2.2.2 Image De-noising Methods 12

2.2.3 Image Compressive Sensing Methods 14

3 New Image Quality Index **19**

3.1 Review of image quality metrics . . . 20

3.1.1 Pixel-Based Mathematical Metrics . . . 20

3.1.2 Visual Signal-to-Noise Ratio . . . 20

3.1.3 Universal Image Quality Index (UIQI) . . . 21

3.1.4 Structural Similarity Index Measure (SSIM) . . . 22

3.1.5 Multi-Scale Structural Similarity (MS-SSIM) . . . 24

3.1.6 Histogram Based Image Quality Index . . . 24

3.2 New Image Quality Index . . . 26

3.3 Evaluation Method . . . 29

3.3.1 Correlation based methods . . . 29

3.3.2 Error Methods . . . 30

3.4 Experimental Results and Discussion . . . 31

3.4.1 List of Image Quality Databases . . . 31

3.4.2 Methodology . . . 37

3.4.3 Experimental Results and Discussions . . . 38

3.5 Summary . . . 41

4 Image Compression **47**

4.1 Wavelet Transform Logical Support . . . 48

4.1.1 Cohen-Daubechies-Feauveau 9/7 (CDF 9/7) Wavelet Transform . . . 52

4.1.2 Orthogonal Discrete Wavelet Transform . . . 55

4.2 Set Partition in Hierarchical Trees (SPIHT) Coding Scheme . . . 56

4.3 Entropy Coding . . . 57

4.4 Proposed Algorithm for Image Compression . . . 59

4.5 Experimental Results and Discussion . . . 60

4.5.1 Daubechies family and CDF 9/7 wavelet with SPIHT . . . 63

4.5.2 Coiflet Family with SPIHT . . . 64

4.5.3 Symlet Family with SPIHT . . . 64

4.5.4 Biorthogonal Family with SPIHT . . . 64

4.5.5 Reverse Biorthogonal Family with SPIHT . . . 65

4.6 Summary . . . 65

5 Image De-noising **73**

5.1 Review . . . 74

5.1.1 Shearlet Transform . . . 74

5.1.2 The Discrete Shearlet Transform . . . 77

5.1.3 Donoho Universal VisuShrink Threshold . . . 82

5.1.4 PID Control Scheme . . . 82

5.2 Image De-noising with Shearlet Transform and Adaptive Shrinkage Threshold . . . 84

5.3 Image De-noising with CDF 9/7 Wavelet Transform . . . 86

5.4 Experimental Results and Discussion . . . 87

5.4.1 De-noising Method with Shearlet Transform . . . 87

5.4.2 De-noising Method with CDF 9/7 Wavelet Transform . . . 90

5.5 Summary . . . 90

6 Image Compressive Sensing **107**

6.1 Compressive Sensing . . . 109

6.2 Sparse Representation of Image . . . 111

6.3 Proposed Image Compression Method Based on Compressive Sensing . . . 113

6.4 Proposed Image De-noising Method Based on Compressive Sensing . . . 113

6.5 Experimental Results and Discussion . . . 115

6.5.1 Image Compression with Compressive Sensing . . . 115

6.5.2 De-noising Method with Compressive Sensing . . . 118

6.6 Summary . . . 120

7 Conclusions **137**

7.1 Research Achievements and Contributions . . . 137

7.2 Suggestions for Further Research . . . 138

Bibliography **141**

A Appendix **163**

A.1 Basis Pursuit . . . 163

A.1.1 Description . . . 163

A.1.2 Restricted Isometric Condition . . . 164

A.2 Greedy Methods 169
A.2.1 Orthogonal Matching Pursuit 169
A.3 Total Variation De-noising Method 171
A.4 Texture Preserving Variational De-noising Using an Adaptive Fidelity Term 172

List of Figures

2.1 Block diagram of typical discrimination/quality metric [1]. 7

2.2 Original test image Lena (a) and its histogram (b). 8

3.1 Block diagram of the structural similarity (SSIM) index measure [2]. 23

3.2 Proposed diagram of the 4^{th} factor structural similarity (SSIM4) quality measure. 26

3.3 Comparison among different image quality indexes with output map between the input and distorted image displayed with brightness indicates the magnitude of the quality index. 41

3.4 Scatter plots of subjective MOS scores versus objective scores obtained by model prediction on the TID2013 database. 43

3.5 Scatter plots of subjective MOS scores versus objective scores obtained by model prediction on the MICT database. 44

3.6 Scatter plots of subjective MOS scores versus objective scores obtained by model prediction on the IVC database. 45

3.7 Scatter plots of subjective MOS scores versus objective scores obtained by model prediction on the WIQ database. 46

4.1 Discrete wavelet transform (or sub-band transform) analysis and synthesis system [3]. . . 48

4.2 The 2-D DWT analysis filter bank [4]. 49

4.3 The 2-D row and column computation of DWT [4]. 49

4.4 The (Left) second and (Right) third level row and column decomposition [4]. 50

4.5 Ployphase representation of wavelet transform [3]. 51

4.6 The lifting-based WT [5]. 52

4.7 Analysis side of CDF 9/7 wavelet using Lifting scheme [5]. 53

4.8 Lifting implementation of the synthesis side of CDF 9/7 wavelet transform [5]. 55

4.9 Huffman encoding technique both (a) and (b) [6]. 59
4.10 Block diagram for proposed image compression. 60
4.11 Compressing of MR image with CDF 9/7 (Lifting scheme) and SPIHT together with Huffman and Run length coding. 67
4.12 Wavelet versus proposed Q and other EIQ methods (Daubechies family and CDF 9/7). . 68
4.13 Wavelet versus proposed Q and other EIQ methods (Coiflet family). 69
4.14 Wavelet versus proposed Q and other EIQ methods (Symlet family). 69
4.15 Wavelet versus proposed Q and other EIQ methods (Biorthogonal family). 70
4.16 Wavelet versus proposed Q and other EIQ methods (Reverse Biorthogonal family). . . . 71
4.17 Compare the compressed of MR image for CDF 9/7 (Lifting scheme) and SPIHT and different mother wavelet with SPIHT. 72

5.1 The structure of the frequency tiling shearlet $\psi_{j,l,k}$. (a) The tiling of horizontal cone is illustrated in the solid lines; the tiling of vertical cone is in the dashed lines. (b) Frequency support of shearlet satisfies parabolic scaling (j-decomposition level). The figure shows only the support for $\xi_1 > 0$; the other half of the support for $\xi_1 < 0$ is symmetrical [7]. 76
5.2 Illustrates the succession of Laplacian pyramid and directional filtering [8]. 81
5.3 A block diagram of the simplest closed-loop system. 83
5.4 A block diagram of the parallel algorithm of PID control structure. 83
5.5 The original 512×512 benchmark test images for the experiments. The experimental 30 images are starting from top left to bottom right 1) Peppers(grey), 2) Lena (grey), 3) Barbara (grey), 4) Boat (grey), 5) Aerial (grey), 6) Airplane-1 (grey), 7) Couple (grey), 8) Elaine (grey), 9) Tank (grey), 10) Truck (grey), 11) CT-1 cancer (grey)., 12) Baboon (grey), 13) Cat (grey), 14) Man (grey), 15) Monkey (grey), 16) Airplane-2 (grey), 17) Heritage (grey), 18) Fish (grey), 19) House (grey), 20) Infrared (grey), 21) X-ray cancer (grey), 22) MR cancer (grey), 23) Lena (colour), 24) Peppers (colour), 25) Barbara (colour), 26) Airplane (colour), 27) Boat (colour), 28) House (colour), 29) Baboon (colour), 30) CT-2 cancer (grey) 92
5.6 Plot of different image quality indexes versus standard deviations (σ) for X-ray image. . 93
5.7 Visual comparison of de-noised X-ray images for the different de-noising methods including proposed de-nosing method (standard deviation (σ) = 10). 94

5.8 Visual comparison of de-noised X-ray images for the different de-noising methods including proposed de-nosing method (standard deviation (σ) = 20). 95

5.9 Visual comparison of de-noised X-ray images for the different de-noising methods including proposed de-nosing method (standard deviation (σ) = 30). 96

5.10 Visual comparison of de-noised X-ray images for the proposed de-nosing method while tuning for optimal parameters. 97

5.11 The relationship between the image quality indexes (UIQI, Q(Skewness) and Q(Kurtosis)) of using proposed de-noising methods for tuning the values l, m and n. 98

5.12 The relationship between the image quality indexes (SSIM, SSIM(Skewness), SSIM(Abs-Skewness) & SSIM(Kurtosis)) of using proposed de-noising methods for tuning the values l, m and n. 99

5.13 Optimal points $(Quality\ Index, m)$ at $l = n = l_{opt} = 1$ as reference with blue dot point and optimal points $(Quality\ Index, l)$ at $m = m_{opt}$ as reference with red dot points for UIQI, Q(Skewness) and Q(Kurtosis) over 30 experimental images. 100

5.14 Optimal points $(Quality\ Index, m)$ at $l = n = l_{opt} = 1$ as reference with blue dot point and optimal points $(Quality\ Index, l)$ at $m = m_{opt}$ as reference with red dot points for SSIM, SSIM(Skewness), SSIM(Abs-Skewness), SSIM(Kurtosis) over 30 experimental images. 101

5.15 Visual comparison of de-noised X-ray images for the proposed de-nosing method while tuning for optimal parameters. 102

5.16 Plot of standard deviation versus different image quality indexes on an Infared image de-noised with different methods, including the proposed methods. 103

5.17 De-noising of Infared (IR) image for standard deviation (σ) = 10. 104

5.18 De-noising of Infared (IR) image for standard deviation (σ) = 20. 105

6.1 Discrete wavelet transform (or subband transform) analysis and synthesis system [3]. . . 112

6.2 Proposed image compression framework based on compressive sensing. 113

6.3 Proposed image de-noising framework based on compressive sensing. 115

6.4 Plots of eight image quality indexes for human body muscle cells image versus number of measurements $(M)(M < N, N = 256)$ in the range $[150 - 250]$ for proposed sparse basis on CDF 9/7 wavelet transform with three measurements matrix and OMP including the sparse basis on DWT. 121

6.5 Plots of eight image quality indexes for human body cellulase cells image versus number of measurements $(M)(M < N, N = 256)$ in the range $[150 - 250]$ for proposed sparse basis on CDF 9/7 wavelet transform with three measurements matrix and OMP including the sparse basis on DWT. 122

6.6 Compressed human body muscle cells image (where $N = 256$ and $M = 190$). 123

6.7 Plots of eight image quality indexes for brain (MR)-1 image versus number of measurements $(M)(M < N, N = 4096)$ in the range $[1500-3500]$ for proposed sparse basis on CDF 9/7 wavelet transform with three measurements matrix and BP including the sparse basis on DCT. 124

6.8 Plots of eight image quality indexes for brain (MR)-2 image versus number of measurements $(M)(M < N, N = 4096)$ in the range $[1500-3500]$ for proposed sparse basis on CDF 9/7 wavelet transform with three measurements matrix and BP including the sparse basis on DCT. 125

6.9 Compressed human brain (MR)-1 image (where $N = 4096$ and $M = 3500$). 126

6.10 Plots of eight image quality indexes for X-ray image versus noise standard deviations (σ) in the range [5, 25] for six different proposed de-noising approach. 127

6.11 Plots of eight image quality indexes for MR image versus noise standard deviations (σ) in the range [5, 25] for six different proposed de-noising approach. 128

6.12 Plots of eight image quality indexes versus noise standard deviations (σ) in the range [5, 25] for six different proposed de-noising approach for heart image. 129

6.13 De-noising of X-ray image for standard deviation (σ) = 5. 130

6.14 De-noising of X-ray image for standard deviation (σ) = 10. 131

6.15 Plots of eight image quality indexes versus noise standard deviations (σ) in the range [5, 25] for six different proposed de-noising approach for brain (MR)-1 image. 132

6.16 Plots of eight image quality indexes versus noise standard deviations (σ) in the range [5, 25] for six different proposed de-noising approach for brain (MR)-2 image. 133

6.17 De-noising of brain (MR)-1 image for standard deviation (σ) = 5. 134

6.18 De-noising of brain (MR)-1 image for standard deviation (σ) = 10. 135

6.19 Comparison of computational complexity for (a) novel compression scheme with CS tested on human body muscle cells image (b) novel de-noising scheme with CS tested on X-ray image 136

6.20 Comparison of computational complexity for (a) novel compression scheme with CS (b) novel de-noising scheme with CS tested on for brain (MR)-1 image. 136

A.1 The minimizers to the mean square (left) and l_1 (right) approaches. 164

List of Tables

3.1 Twenty-three publicly available image quality databases. 32
3.2 Evaluation of image quality (EIQ) models over TID2013 database. 39
3.3 Evaluation of image quality (EIQ) models over MICT database. 39
3.4 Evaluation of image quality (EIQ) models over IVC database. 40
3.5 Evaluation of image quality (EIQ) models over WIQ database. 40
3.6 Time cost of each EIQ index. 42

4.1 Image quality indexes of recovered image using decomposition with CDF 9/7 wavelet transform (WT) (Lifting based) with SPIHT, Huffman coding & Run length coding. . . . 61
4.2 Image quality indexes and compression ratio (CR) of recovered image using decomposition with CDF 9/7 WT (Lifting based) with SPIHT, Huffman coding & Run length coding. 62
4.3 Image quality indexes of CDF 9/7 WT (Lifting based) with SPIHT. 62
4.4 Image quality indexes and compression ratio (CR) of CDF 9/7 WT (Lifting based) with SPIHT. 62
4.5 Image quality indexes of CDF 9/7 WT (Lifting based) with SPIHT & Huffman coding. . 62
4.6 Image quality indexes and compression ratio (CR) of CDF 9/7 WT (Lifting based) with SPIHT & Huffman coding. 63
4.7 Image quality indexes CDF 9/7 WT (Lifting based) with SPIHT, Huffman coding & Run length coding. 63
4.8 Image quality indexes and compression ratio (CR) CDF 9/7 WT (Lifting based) with SPIHT, Huffman coding & Run length coding. 63