Despeckle Filtering for Ultrasound Imaging and Video

Volume I

Algorithms and Software

Second Edition

Christos P. Loizou
School of Sciences and Engineering, Intercollege, Cyprus

Constantinos S. Pattichis
University of Cyprus

SYNTHESIS LECTURES ON ALGORITHMS AND SOFTWARE IN ENGINEERING #14

MORGAN & CLAYPOOL PUBLISHERS

ABSTRACT

It is well known that speckle is a multiplicative noise that degrades image and video quality and the visual expert's evaluation in ultrasound imaging and video. This necessitates the need for robust despeckling image and video techniques for both routine clinical practice and tele-consultation. The goal for this book (book 1 of 2 books) is to introduce the problem of speckle occurring in ultrasound image and video as well as the theoretical background (equations), the algorithmic steps, and the MATLAB™ code for the following group of despeckle filters: linear filtering, nonlinear filtering, anisotropic diffusion filtering, and wavelet filtering. This book proposes a comparative evaluation framework of these despeckle filters based on texture analysis, image quality evaluation metrics, and visual evaluation by medical experts. Despeckle noise reduction through the application of these filters will improve the visual observation quality or it may be used as a pre-processing step for further automated analysis, such as image and video segmentation, and texture characterization in ultrasound cardiovascular imaging, as well as in bandwidth reduction in ultrasound video transmission for telemedicine applications. The aforementioned topics will be covered in detail in the companion book to this one. Furthermore, in order to facilitate further applications we have developed in MATLAB™ two different toolboxes that integrate image (IDF) and video (VDF) despeckle filtering, texture analysis, and image and video quality evaluation metrics. The code for these toolsets is open source and these are available to download complementary to the two books.

KEYWORDS

speckle, despeckle, noise filtering, ultrasound, ultrasound imaging, ultrasound video, cardiovascular imaging and video, SAR, texture, image quality, video quality, carotid artery

References

[1] B. Fetics et al., "Enhancement of contrast echocardiography by image variability analysis," *IEEE IEEE Trans. Med. Imag.*, vol. 20, no. 11, pp. 1123–1130, Nov. 2001. DOI: 10.1109/42.963815. 2, 10, 11, 126

[2] C.I. Christodoulou, C. Loizou, C.S. Pattichis, M. Pantziaris, E. Kyriakou, M.S. Pattichis, C.N. Schizas, and A. Nicolaides,"Despeckle filtering in ultrasound imaging of the carotid artery," *Second Joint EMBS/BMES Conference*,Houston, TX, USA, pp. 1027–1028, Oct. 23–26, 2002. DOI: 10.2200/S00116ED1V01Y200805ASE001. 2, 18, 19, 124

[3] K. Abd-Elmoniem, A.-B. Youssef, and Y. Kadah, "Real-time speckle reduction and coherence enhancement in ultrasound imaging via nonlinear anisotropic diffusion," *IEEE Trans. Biomed. Eng.*, vol. 49, no. 9, pp. 997–1014, Sept. 2002. DOI: 10.1109/TBME.2002.1028423. 10, 11, 16, 17, 20, 41, 42, 86, 92, 94, 124, 126

[4] J.E. Wilhjelm, M.S. Jensen, S.K. Jespersen, B. Sahl, and E. Falk, "Visual and quantitative evaluation of selected image combination schemes in ultrasound spatial compound scanning," *IEEE Trans. Med. Imag.*, vol. 23, no. 2, pp. 181–190, 2004. DOI: 10.1109/TMI.2003.822824. 2, 10

[5] A. Achim, A. Bezerianos and P. Tsakalides, "Novel Bayesian multiscale method for speckle removal in medical ultrasound images," *IEEE Trans. Med. Imag.*, vol. 20, no. 8, pp. 772–783, 2001. DOI: 10.1109/42.938245. 2, 11, 16, 17, 41, 97, 124, 126

[6] C. Christodoulou, C. Pattichis, M. Pantziaris, and A. Nicolaides, "Texture-Based Classification of Atherosclerotic Carotid Plaques," *IEEE Trans. Med. Imag.*, vol. 22, no. 7, pp. 902–912, 2003. DOI: 10.1109/TMI.2003.815066. 2

[7] T. Elatrozy, A. Nicolaides, T. Tegos, A. Zarka, M. Griffin, and M. Sabetai, "The effect of B-mode ultrasonic image standardization of the echodensity of symptomatic and asymptomatic carotid bifurcation plaque," *Int. Angiology*, vol. 17: 179–186, no. 3, Sept. 1998. 2, 10, 12, 17, 20, 23, 34, 41, 57, 58, 79, 86, 124, 125, 126

[8] C.P. Loizou, C.S. Pattichis, M. Pantziaris, T. Tyllis, and A. Nicolaides, "Quantitative quality evaluation of ultrasound imaging in the carotid artery," *Med. Biol. Eng. & Comput.*," vol. 44, no. 5, pp. 414–426, 2006. DOI: 10.1007/s11517-006-0045-1. 10, 20, 34, 38

[9] C.P. Loizou, C.S. Pattichis, M. Pantziaris, and A. Nicolaides, "An integrated system for the segmentation of atherosclerotic carotid plaque," *IEEE Trans. Inform. Techn. Biomed.*," vol. 11, no. 5, pp. 661–667, Nov. 2007. DOI: 10.1109/TITB.2006.890019. 10, 17, 34, 129

[10] C.I. Christodoulou, S.C. Michaelides, and C.S. Pattichis, "Multi-feature texture analysis for the classification of clouds in satellite imagery," *IEEE Trans. Geoscience & Remote Sens.*, vol. 41, no. 11, pp. 2662–2668, Nov. 2003. DOI: 10.1109/TGRS.2003.815404.

[11] C.P. Loizou, C.S. Pattichis, C.I. Christodoulou, R.S.H. Istepanian, M. Pantziaris, and A. Nicolaides "Comparative evaluation of despeckle filtering in ultrasound imaging of the carotid artery," *IEEE Trans. Ultr. Fer. Freq. Contr.*, vol. 52, no. 10, pp. 1653–1669, 2005. DOI: 10.1109/TUFFC.2005.1561621.

[12] C.P. Loizou, V. Murray, M.S. Pattichis, M. Pantziaris, A.N. Nicolaides, and C.S. Pattichis, "Despeckle filtering for multiscale amplitude-modulation frequency-modulation (AM-FM) texture analysis of ultrasound images of the intima-media complex," *Int. J. Biomed. Imag.*, vol. 2014, Art. ID. 518414, 13 pages, 2014. DOI: 10.1155/2014/518414. 20, 26, 79

[13] C.P. Loizou, C. Theofanous, M. Pantziaris, and T. Kasparis, "Despeckle filtering software toolbox for ultrasound imaging of the common carotid artery," *Comput. Meth. & Progr. Biomed.,* vol. 114, no. 1, pp. 109–124, 2014. DOI: 10.1016/j.cmpb.2014.01.018. 2, 11, 12, 26, 31, 32, 33, 34, 41, 42, 79, 80, 81, 83, 134, 135

[14] C.P. Loizou, S. Petroudi, C.S. Pattichis, M. Pantziaris, and A.N. Nicolaides, "An integrated system for the segmentation of atherosclerotic carotid plaque in ultrasound video," *IEEE Trans. Ultras. Ferroel. Freq. Contr.,* vol. 61, no. 1, pp. 86–101, 2014. DOI: 10.1109/TUFFC.2014.6689778. 2, 10, 11, 23, 26

[15] C.P. Loizou, C. Theofanous, M. Pantziaris, T. Kasparis, P. Christodoulides, A.N. Nicolaides, and C.S. Pattichis, "Despeckle filtering toolbox for medical ultrasound video," *Int. J. Monitoring & Surveill. Technol. Resear.(IJMSTR): Special issue Biomed. Monitor. Technol.,* vol. 4, no. 1, pp. 61–79, 2013. DOI: 10.4018/ijmstr.2013100106. 2, 11, 12, 20, 26, 34, 37, 134, 135

[16] K.T. Dussik, "On the possibility of using ultrasound waves as a diagnostic aid," *Neurol. Psychiat.,* vol. 174, pp. 153–168, 1942. DOI: 10.1007/BF02877929. 2

[17] A. Kurjak, "Ultrasound scanning - Prof. Ian Donald (1910–1987)," *Eur. Journal Obstet. Gynecol. Reprod. Biol.*, vol. 90, no. 2, pp. 187-189, Jun. 2000. DOI: 10.1016/S0301-2115(00)00270-0. 2

[18] S.-M. Wu, Y.-W. Shau, F.-C. Chong, and F.-J. Hsieh, "Non-invasive assessment of arterial dimension waveforms using gradient-based Hough transform and power Doppler ultrasound imaging," *Journal of Med. Biol. Eng. & Comp.*, vol. 39, pp. 627–632, 2001. DOI: 10.1007/BF02345433. 4

[19] R. Gonzalez and R. Woods, *Digital image processing,* Second Edition, Prentice-Hall Inc., 2002. 4, 17, 19, 35, 68, 69

[20] W.R. Hedrick and D.L. Hykes, "Image and Signal Processing in Diagnostic Ultrasound Imaging," *J. Diagnostic Med. Sonogr.*, vol. 5, no. 5, pp. 231–239, 1989. DOI: 10.1177/875647938900500502. 7, 8

[21] F.J. Polak, *Doppler Sonography: An Overview, In Peripheral Vascular Sonography: A Practical Guide,* Baltimore USA: Williams and Wilkins, 1992. 7, 8, 10

[22] A Philips Medical System Company, "Comparison of image clarity, SonoCT real-time compound imaging versus conventional 2D ultrasound imaging," *ATL Ultrasound, Report*, 2001. 8, 10

[23] J.-C. Tradif and H. Lee, "Applications of ultravasular ultrasound in cardiology, What's new in cardiovascular ultrasound imaging," J. Reiber and E. van der Wall, Eds., pp. 133–148, Dordrecht: Kluwer Academic Publisher, 1998. 9

[24] M. Cilingiroglu, A. hakeem, M. Feldman, and M. Wholey, "Optical coherence tomography imaging in asymptomatic patients with carotid artery stenosis," *Cardiovascular Revascularization in Medicine*, vol. 14, no. 1, pp. 53–56, 2012. DOI: 10.1016/j.carrev.2012.09.004. 9, 85

[25] C.P. Loizou, C.S. Pattichis, M. Pantziaris, T. Tyllis, and A. Nicolaides, "Snakes based segmentation of the common carotid artery intima media," *Med. Biol. Eng. & Comput.*," vol. 45, no. 1, pp. 35–49, Jan. 2007. DOI: 10.1007/s11517-006-0140-3. 10, 17, 34, 115, 116, 117, 118, 129

[26] C.S. Pattichis, C. Christodoulou, E. Kyriakou, M. Pantziaris, A. Nicolaides, M.S. Pattichis, and C.P. Loizou, "Ultrasound imaging of carotid atherosclerosis," in *Wiley encyclopaedia of Biomedical Engineering*, Ed. By M. Akay, Wiley, Hoboken: John Wiley & Sons, Inc., USA, 2006. DOI: 10.1002/9780471740360.ebs1322. 10

[27] P. Rerona and J. Malik, "Scale-space and edge detection using anisotropic diffusion," *IEEE Trans. Pattern Anal. & Mach. Intellig.*, vol. 12, no. 7, pp. 629–639, July 1990. DOI: 10.1109/34.56205. 11, 17, 20, 85, 86, 125

[28] X. Hao, S. Gao, and X. Gao, "A novel multiscale nonlinear thresholding method for ultrasonic speckle suppressing," *IEEE Trans. Med. Imag.*, vol. 18, no. 9, pp. 787–794, 1999. DOI: 10.1109/42.802756. 11, 16, 17, 20, 23, 124, 126, 127

[29] Y. Yongjian and S.T. Acton, "Speckle reducing anisotropic diffusion," *IEEE Trans. Image Proces.*, vol. 11, no. 11, pp. 1260–1270, Nov. 2002. DOI: 10.1109/TIP.2002.804276. 11, 12, 17, 20, 23, 41, 85, 87, 88, 124, 125, 126

[30] D. Lamont, L. Parker, M. White, N. Unwin et al., "Risk of cardiovascular disease measured by carotid intima-media thickness at age 49–51: life course study," *BMJ*, vol. 320, pp. 273–278, 29 Jan. 2000. DOI: 10.1136/bmj.320.7230.273. 10

[31] C.P. Loizou, T. Kasparis, P. Papakyriakou, L. Christodoulou, M. Pantziaris, and C.S. Pattichis, "Video segmentation of the common carotid artery intima-media complex," *12th Int. Conf. Bioinf. & Bioeng. Proc. (BIBE)*, Larnaca, Cyprus, Nov. 11–13, pages 4, 2012. DOI: 10.1109/BIBE.2012.6399728. 10, 11

[32] C.B. Burckhardt, "Speckle in ultrasound B-mode scans," *IEEE Trans. Sonics Ultrasonics*, vol. SU-25, no. 1, pp. 1–6, 1978. DOI: 10.1109/T-SU.1978.30978. 11, 12, 17, 19, 20, 42, 86

[33] R.F. Wagner, S.W. Smith, J.M. Sandrik, and H. Lopez, "Statistics of speckle in ultrasound B-scans," *IEEE Trans. Sonics Ultrasonics*, vol. 30, pp. 156–163, 1983. DOI: 10.1109/T-SU.1983.31404. 11, 14, 16

[34] J.W. Goodman, "Some fundamental properties of speckle," *J. Optical Society of America*, vol. 66, no. 11, pp. 1145–1149, 1976. DOI: 10.1364/JOSA.66.001145. 11, 12, 14, 17

[35] R.W. Prager, A.H. Gee, G.M. Treece, and L. Berman, "Speckle detection in ultrasound images using first order statistics." University of Cambridge, Dept. of Engineering, GUED/F-INFENG/TR 415, pp. 1–17, July 2002. 11, 12, 42

[36] J.S. Lee, "Speckle analysis and smoothing of synthetic aperture radar images," *Computer Graph. Image Proces.*, vol. 17, pp. 24–32, 1981. DOI: 10.1016/S0146-664X(81)80005-6. 17, 18, 19, 41, 87, 124, 127

[37] C.P. Loizou, T. Kasparis, P. Christodoulides, C. Theofanous, M. Pantziaris, E. Kyriakou, and C.S. Pattichis, "Despeckle filtering in ultrasound video of the common carotid artery," *12th Int. Conf. Bioinf. & Bioeng. Proc. (BIBE)*, Larnaca, Cyprus, Nov. 11–13, pages 4, 2012. DOI: 10.1109/BIBE.2012.6399756. 11, 20, 26, 31, 42

[38] J.S. Lee, "Digital image enhancement and noise filtering by using local statistics," *IEEE Trans. Pattern Analysis & Machine Intellig.*, PAMI-2, no. 2, pp. 165–168, 1980. DOI: 10.1109/TPAMI.1980.4766994. 11, 17, 18, 19, 23, 41, 87, 124, 125

[39] M. Black, G. Sapiro, D. Marimont, and D. Heeger, "Robust anisotropic diffusion," *IEEE Trans. Image Proces.*, vol. 7, no. 3, pp. 421–432, March 1998. DOI: 10.1109/83.661192. 17, 85, 86, 124

[40] V. Dutt, "Statistical analysis of ultrasound echo envelope," Ph.D. dissertation, Mayo Graduate School, Rochester, MN, 1995. 11, 12, 14, 15, 16, 26, 37, 42, 124

[41] M. Insana et al., "Progress in quantitative ultrasonic imaging," *SPIE Vol. 1090 Medical Imaging III, Image Formation*, pp. 2–9, 1989. DOI: 10.1117/12.953184. 12, 17, 20

[42] J.C. Dainty, *Laser speckle and related phenomena,* Springer-Verlag, Berlin Heidelberg, New York, 1974. 12, 13, 14, 37

[43] J.M. Thijssen, B.J. Oosterveld, P.C. Hartman et al., "Correlations between acoustic and texture parameters from RF and B-mode liver echograms," *Ultrasound Med. Biol.*, vol. 19, pp. 13–20, 1993. DOI: 10.1016/0301-5629(93)90013-E. 12

[44] L. Busse, T.R. Crimmins, and J.R. Fienup, "A model based approach to improve the performance of the geometric filtering speckle reduction algorithm," *IEEE Ultrasonic Symposium*, pp. 1353–1356, 1995. DOI: 10.1109/ULTSYM.1995.495807. 14, 17, 18, 19, 23, 72

[45] J.U. Quistgaard, "Signal acquisition and processing in medical diagnostic ultrasound," *IEEE Signal Proces. Magazine*, vol. 14, no. 1, pp. 67–74, Jan. 1997. DOI: 10.1109/79.560325. 15

[46] H. Paul and H.P. Schwann, "Mechanism of absorption of ultrasound in liver tissue," *J. Acoustical Society America*, vol. 50, pp. 692, 1971. DOI: 10.1121/1.1912685. 14, 17, 18, 41

[47] V.S. Frost, J.A. Stiles, K.S. Shanmugan, and J.C. Holtzman, "A model for radar images and its application for adaptive digital filtering of multiplicative noise," *IEEE Trans. Pattern Analysis & Machine Intellig.*, vol. 4, no. 2, pp. 157–165, 1982. DOI: 10.1109/TPAMI.1982.4767223. 17, 18, 19, 20, 42, 69, 87, 124, 125

[48] J.S. Lee, "Refined filtering of image noise using local statistics," *Computer Graph. & Image Proces.*, vol. 15, pp. 380–389, 1981. DOI: 10.1016/S0146-664X(81)80018-4. 17, 18, 19, 41, 87, 124

[49] D.T. Kuan, A.A. Sawchuk, T.C. Strand, and P. Chavel, "Adaptive restoration of images with speckle," *IEEE Trans. Acoustic Speech & Signal Processing*, vol. ASSP-35, pp. 373–383, 1987. DOI: 10.1109/TASSP.1987.1165131. 17

[50] D.T. Kuan and A.A. Sawchuk, "Adaptive noise smoothing filter for images with signal dependent noise," *IEEE Trans. Pattern Analysis & Mach. Intellig.*, vol. PAMI-7, no. 2, pp. 165–177, 1985. DOI: 10.1109/TPAMI.1985.4767641. 17, 18, 19, 20, 41, 124

[51] C.P. Loizou , C. Christodoulou, C.S. Pattichis, R. Istepanian, M. Pantziaris, and A. Nicolaides, "Speckle reduction in ultrasound images of atherosclerotic carotid plaque," *DSP*

2002, Proc. IEEE 14th Int. Conf. Digital Signal Proces., Santorini-Greece, pp. 525–528, July 1–3, 2002. DOI: 10.1109/ICDSP.2002.1028143. 17, 18, 19, 20, 78, 124, 126

[52] X. Zong, A. Laine, and E. Geiser, "Speckle reduction and contrast enhancement of echocardiograms via multiscale nonlinear processing," *IEEE Trans. Med. Imag.*, vol. 17, no. 4, pp. 532–540, 1998. DOI: 10.1109/42.730398. 17, 97, 126, 127

[53] M. Karaman, M. Alper Kutay, and G. Bozdagi, "An adaptive speckle suppression filter for medical ultrasonic imaging," *IEEE Trans. Med. Imag.*, vol. 14, no. 2, pp. 283–292, 1995. DOI: 10.1109/42.387710. 17, 126, 127

[54] S.M. Ali and R.E. Burge, "New automatic techniques for smoothing and segmenting SAR images," *Signal Processing*, North-Holland, vol. 14, pp. 335–346, 1988. DOI: 10.1016/0165-1684(88)90092-8. 17, 70, 124

[55] A. Baraldi and F. Pannigianni, "A refined gamma MAP SAR speckle filter with improved geometrical adaptivity," *IEEE Trans. Geoscience & Remote Sensing*, vol. 33, no. 5, pp. 1245–1257, Sep. 1995. DOI: 10.1109/36.469489.

[56] E. Trouve, Y. Chambenoit, N. Classeau, and P. Bolon, "Statistical and operational performance assessment of multi-temporal SAR image filtering," *IEEE Trans. Geosc. & Remote Sens.*, vol. 41, no. 11, pp. 2519–2539, 2003. DOI: 10.1109/TGRS.2003.817270. 17, 124

[57] H.-L. Eng and K.-K. Ma, "Noise adaptive soft-switching median filter," *IEEE Trans. Image Process.*, vol. 10, no. 2, pp. 242–251, 2001. DOI: 10.1109/83.902289. 17, 126, 127

[58] S. Solbo and T. Eltoft, "Homomorphic wavelet based-statistical despeckling of SAR images," *IEEE Trans. Geosc. Remote Sensing*, vol. 42, no. 4, pp. 711–721, 2004. DOI: 10.1109/TGRS.2003.821885. 17

[59] J. Saniie, T. Wang, and N. Bilgutay, "Analysis of homomorphic processing for ultrasonic grain signal characterization," *IEEE Trans. Ultr., Fer. & Freq. Contr.*, vol. 3, pp. 365–375, 1989. DOI: 10.1109/58.19177. 17, 18, 19, 78

[60] T. Huang, G. Yang, and G. Tang, "A fast two-dimensional median filtering algorithm," *IEEE Trans. Acoustics, Speech & Sign. Proces.*, vol. 27, no. 1, pp. 13–18, 1979. DOI: 10.1109/TASSP.1979.1163188. 17, 19, 20, 67, 85, 124

[61] J. Weickert, B. Romery, and M. Viergever, "Efficient and reliable schemes for nonlinear diffusion filtering," *IEEE Trans. Image Proces.*, vol. 7, pp. 398–410, 1998. DOI: 10.1109/83.661190. 17, 20, 56, 85

[62] S. Jin, Y. Wang, and J. Hiller, "An adaptive non-linear diffusion algorithm for filtering medical images," *IEEE Trans. Inf. Techn. Biomed.*, vol. 4, no. 4, pp. 298–305, Dec. 2000. DOI: 10.1109/4233.897062. 17

[63] M. Larsson, B. Heyde, F. Kremer, L.-A. Brodin, and J. D'hooge, "Ultrasound speckle tracking for radial, longitudinal and circumferential strain estimation of the carotid artery – An in vitro validation via sonomicrometry using clinical and high-frequency ultrasound," *Ultrasonics*", accepted. DOI: 10.1016/j.ultras.2014.09.005. 17, 18

[64] J. D'hooge, E. Konofagou, F. Jamal, A. Heimdal, L. Barrios, B. Bijnens, J. Thoen, F. Van de Werf, G. Sutherland, and P. Suetens, "Two-dimensional ultrasonic strain rate measurement of the human heart in Vivo," *IEEE Trans. Ultras. Fer. Freq. Contr.*, vol. 49, pp. 281–286, 2002. DOI: 10.1109/58.985712. 17

[65] C.L. de Korte, H.H. Hansen, A.F. and van der Steen, "Vascular ultrasound for atherosclerosis imaging," *Interf. Focus*, vol. 1, pp. 565–575, 2001. DOI: 10.1098/rsfs.2011.0024. 17

[66] M. Catalano, A. Lamberti-Castronuovo, A. Catalano, D. Filocamo, and C. Zimbalatti, "Two-dimensional speckle-tracking strain imaging in the assessment of mechanical properties of carotid arteries: feasibility and comparison with conventional markers of subclinical atherosclerosis," *Eur. J. Echocardiogr.*, vol. 12, pp. 528–535, 2001. DOI: 10.1093/ejechocard/jer078. 17, 18

[67] M. Cinthio, Å. Rydén Ahlgren, T. Jansson, A. Eriksson, H.W. Persson, and L. Kjell, "Evaluation of an ultrasonic echo-tracking method for measurements of arterial wall movements in two dimensions," *IEEE Trans. Ultr. Fer. Freq. Contr.*, vol. 52, pp. 1300–1311, 2005. DOI: 10.1109/TUFFC.2005.1509788. 18

[68] M. Larsson, F. Kremer, P. Claus, T. Kuznetsova, L.-Å. Brodin, and J. D'hooge, "Ultrasound-based Radial and Longitudinal Strain Estimation of the Carotid Artery: a feasibility study," *IEEE Trans. Ultr. Fer. Freq. Contr.*, vol. 58, pp. 2244–2251, 2011. DOI: 10.1109/TUFFC.2011.2074. 18

[69] R. Bernardes, C. Mduro, P. Serranho, A. Araujo, S. Barbeiro, and J. Cunha-Vaz, "Improved adaptive complex diffusion despeckling filter," *Opt. Express*, vol. 18, pp. 24048–24059, 2010. DOI: 10.1364/OE.18.024048. 18, 20, 69, 94

[70] S. Zhong and V. Cherkassky, "Image denoising using wavelet thresholding and model selection," *Proc. of IEEE Int. Conf. Image Proces.*, Vancouver, Canada, pp. 1–4, Nov. 2000. DOI: 10.1109/ICIP.2000.899365. 20, 23, 42, 97

[71] D.L. Donoho, "Denoising by Soft Thresholding," *IEEE Trans. Inform. Theory*, vol. 41, pp. 613–627, 1995. DOI: 10.1109/18.382009. 20, 23, 26, 97, 126, 127

[72] T.W. Chan, O.C. Au, T.S. Chong, and W.S. Chau, "A novel content-adaptive video denoising filter," *Proc. IEEE Vision, Imag. & Sign. Proces.*, vol. 2, no. 2, pp. 649–652, 2005. DOI: 10.1109/ICASSP.2005.1415488. 20

[73] K. Dabov, A. Foi, and K. Egiazarian, "Video denoising by sparse 3D transform-domain collaborative filtering," *Proc. 15th Eur. Sign. Proc. Conf.*, pp. 1–5, 2007.

[74] M. Maggioni, G. Boracchi, A. Foi, and K. Engiazarian, "Video denoising, deblocking and enhancement through separable 4-D nonlocal spatiotemporal transforms," *IEEE Trans. Imag. Proc.*, vol. 21, no. 9, pp. 3952–3966, 2012. DOI: 10.1109/TIP.2012.2199324.

[75] D. Rusanovskyy, K. Dabov, and K. Egiazarian, "Moving-window varying size 3D transform-based video denoising," *Proc. Int. Workshop on Video Proc. & Quality Metrics*, 1–4, 2006.

[76] V. Zlokolica, W. Philips, and van de Ville, "Robust non-linear filtering for video processing," *IEEE Proc. Vision, Imag. & Sign. Proces.*, vol. 2, no. 2, pp. 571–574, 2002. DOI: 10.1109/ICDSP.2002.1028154.

[77] V. Zlokolica, A. Pizurica, and W. Philips, "Recursive temporal denoising and motion estimation of video," *Int. Conf. on Image Proces.*, vol. 3, no. 3, pp. 1465–1468, 2008. DOI: 10.1109/ICIP.2004.1421340. 20

[78] C.P. Loizou and C.S. Pattichis, *Despeckle filtering algorithms and Software for Ultrasound Imaging. Synthesis lectures on algorithms and software for engineering,* Ed. Morgan & Claypool Publishers, San Rafael, CA, USA, 2008. DOI: 10.2200/S00116ED1V01Y200805ASE001. 20, 41, 42, 79

[79] M. Nagao and T. Matsuyama, "Edge preserving smoothing," *Computer Graph. & Image Proces.*, vol. 9, pp. 394–407, 1979. DOI: 10.1016/0146-664X(79)90102-3. 19, 59

[80] T. Greiner, C.P. Loizou, M. Pandit, J. Mauruschat, and F.W. Albert, "Speckle reduction in ultrasonic imaging for medical applications," *Proc. of the ICASSP91, 1991 Int. Conf. Acoustic Signal Speech Processing*, Toronto Canada, May 14–17, pp. 2993-2996, 1991. DOI: 10.1109/ICASSP.1991.151032. 19

[81] A. Nieminen, P. Heinonen, Y. Neuvo, "A new class of detail-preserving filters for image processing," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 9, pp. 74–90, 1987. DOI: 10.1109/TPAMI.1987.4767873. 19, 79

[82] M. Kuwahara, K. Hachimura, S. Eiho, and M. Kinoshita, *Digital processing of biomedical images,* Plenum. Pub. Corp., Ed. K. Preston and M. Onoe, pp. 187–203, 1976. 19, 80

[83] A. Buades, B. Coll, and J.-M. Morel, "Nonlocal image and movie denosing," *Int. J. Comput. Vis.*, vol. 76, pp. 123–139, 2008. DOI: 10.1007/s11263-007-0052-1. 19, 82, 83

[84] A.M. Wink and J.B.T.M. Roerdink, "Denoising functional MR images: A comparison of wavelet denoising and Gaussian smoothing," *IEEE Trans. Med. Imag.*, vol. 23, no. 3, pp. 374–387, 2004. DOI: 10.1109/TMI.2004.824234. 20

[85] N. Rougon and F. Preteux, "Controlled anisotropic diffusion," *Conf. on Nonlinear Image Processing VI*, IS&T/SPIE Symposium on Electronic Imaging, Science and Technology, San Jose, California, pp. 1–12, 5–10 Feb. 1995. DOI: 10.1117/12.205235. 20, 126

[86] F.N.S. Medeiros, N.D.A. Mascarenhas, R.C.P Marques, and C.M. Laprano, "Edge preserving wavelet speckle filtering," *5th IEEE Southwest Symp. Image Anal. & Interpr.*, Santa Fe, New Mexico, pp. 281–285, 7–9 April 2002. DOI: 10.1109/IAI.2002.999933. 20

[87] P. Moulin, "Multiscale image decomposition and wavelets," in *Handbook of Image & Video Processing*, Ed. by A. Bovik, Academic Press, pp. 289–300, 2000. 23

[88] P. Scheunders, "Wavelet thresholding of multivalued images," *IEEE Trans. Image Proces.*, vol. 13, no. 4, pp. 475–483, 2004. DOI: 10.1109/TIP.2004.823829. 23

[89] Christos P. Loizou, PhD thesis, "Ulytrasound image processing for the evaluation of the risk of stroke," Kingston University, UK, 2005. 29, 97

[90] J.T. Bushberg, J. Anthony Seibert, E.M. Leidholdt, Jr., and J.M. Boone, *The essential physics of medical imaging,* Lippincott Williams & Wilkins, 2002. 29

[91] J. Stoitsis, S. Golemati, V. Koropouli, and K.S. Nikita, "Simulating dynamic B-mode ultrasound image data of the common carotid artery," *IEEE Int. Work. Imag. Synth. & Techn.*, pages 4, 2008. DOI: 10.1109/IST.2008.4659958. 31

[92] E. Krupinski, H. Kundel, P. Judy, and C. Nodine, "The medical image perception society, key issues for image perception research," *Radiology*, vol. 209, pp. 611–612, 1998. DOI: 10.1148/radiology.209.3.9844649. 32, 39

[93] Z. Wang, A. Bovik, H. Sheikh, and E. Simoncelli, "Image quality assessment: From error measurement to structural similarity," *IEEE Trans. Image Proces.*, vol. 13, no. 4, pp. 600–612, Apr. 2004. DOI: 10.1109/TIP.2003.819861. 34, 35, 36, 39

[94] A. Ahumada and C. Null, "Image quality: A multidimensional problem," in *Digital images and human vision*, Ed. A.B. Watson, Bradford Press: Cambridge Mass, pp. 141–148, 1993. 34

[95] E.A. Fedorovskaya, H. De Ridder, and F.J. Blomaert, "Chroma variations and perceived quality of colour images and natural scenes," *Color Research & Application*, vol. 22, no. 2, pp. 96–110, 1997. DOI: 10.1002/(SICI)1520-6378(199704)22:2%3C96::AID-COL5%3E3.0.CO;2-Z. 34

[96] G. Deffner, "Evaluation of display image quality: Experts vs. non-experts," *Symposium Society for Information and Display Digest*, vol. 25, pp. 475–478, 1994. 34

[97] T.J. Chen, K.S. Chuang, Jay Wu, S.C. Chen, I.M. Hwang, and M.L. Jan, "A novel image quality index using Moran I statistics," *Physics Med. & Biol.*, vol. 48, pp. 131–137, 2003. DOI: 10.1088/0031-9155/48/8/402. 35

[98] S. Winkler, "Vision models and quality metrics for image processing applications," PhD, University of Lausanne-Switzerland, Dec. 21, 2000. 35, 39

[99] D. Sakrison, "On the role of observer and a distortion measure in image transmission," *IEEE Trans. Communic.,* vol. 25, pp. 1251–1267, Nov. 1977. DOI: 10.1109/TCOM.1977.1093773. 36

[100] Z. Wang and A. Bovik, "A Universal quality index," *IEEE Sign. Proces. Letters*, vol. 9, no. 3, pp. 81–84, March 2002. DOI: 10.1109/97.995823. 36

[101] V.S. Vora, A.C. Suthar, Y.N. Makwana, and S.J. Davda, "Analysis of compresed image quality assessments," *Int. Journal of Advanced Engineering and Applications*, vol. 1, pp. 225–229, 2010. 37, 38

[102] A. Pommert and K. Hoehne, "Evaluation of image quality in medical volume visualization: The state of the art," Takeyoshi Dohi, Ron Kikinis (Eds.): in *Medical image computing and computer-assisted intervention, Proc. MICCAI, 2002, Part II, Lecture Notes in Computer Science 2489,* pp. 598–605, Springer Verlag, Berlin 2002. DOI: 10.1007/3-540-45787-9_75. 39

[103] M. Eckert, "Perceptual quality metrics applied to still image compression," Canon information systems research, Faculty of engineering, Univ. Of Technology, Sydney, Australia, pp. 1–26, 2002. DOI: 10.1016/S0165-1684(98)00124-8. 39

[104] A. Efros, T. Leung, "Texture synthesis by non parametric sampling," *Proc. Int. Conf. Computer Vision*, vol. 2, pp. 1033–1038, 1999. DOI: 10.1109/ICCV.1999.790383. 82

[105] Y. Zhan, M. Ding, L. Wu, and X. Zhang, "Nonlocal means method using wight refining for despeckling for ultrasound images," *Sign. Proc.*, vol. 103, pp. 201–213, 2014. DOI: 10.1016/j.sigpro.2013.12.019. 82, 83

[106] A. Buades, B. Coll, and J. Morel, "On image denoising methods," Technical Report, CMLA, 2004–15. 83

[107] G. Gilboa, N. Sochen, and Y.Y. Zeevi, "Image enhancement and denoising by complex diffusion processes," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 26, no. 8, pp. 1020–1036, 2004. DOI: 10.1109/TPAMI.2004.47. 94

[108] R.N. Czerwinski, D.L. Jones, and W.D. O'Brien, "Detection and boundaries in speckle images-Application to medical ultrasound," *IEEE Trans. Med. Imag.*, vol. 18, no. 2, pp. 126–136, Feb. 1999. DOI: 10.1109/42.759114. 126

[109] A.M. Wink and J.B.T.M. Roerdink, "Denoising functional MR images: A comparison of wavelet denoising and Gaussian smoothing," *IEEE Trans. Med. Imag.*, vol. 23, no. 3, pp. 374–387, 2004. DOI: 10.1109/TMI.2004.824234. 126

[110] S. Jin, Y. Wang, and J. Hiller, "An adaptive non-linear diffusion algorithm for filtering medical images," *IEEE Trans. Inform. Technol. Biomed.*, vol. 4, no. 4, pp. 298–305, Dec. 2000. DOI: 10.1109/4233.897062. 126

[111] V. Damerjian, O. Tankyevych, N. Souag, and E. Petit, "Speckle characterisation methods in ultrasound images-A review," *Innovat. & Resear. Biomed. Eng. (IRBM)*, vol. 35, pp. 202–213, 2014. DOI: 10.1016/j.irbm.2014.05.003. 5, 127

[112] J.A. Noble, "Ultrasound image segmentation and tissue characterization," *Proc. Inst. Mech. Eng.*, vol. 224, no. 2, pp. 307–316, 2010. DOI: 10.1243/09544119JEIM604. 127

[113] C.P. Loizou, "A review on ultrasound common carotid artery image and video segmentation techniques," *Med. Biol. Eng. Comput.*, vol. 52, no. 12, pp. 1073–1093, 2014. DOI: 10.1007/s11517-014-1203-5. 129

[114] R.J. Housden, A.H. Gee, G.M. Treece, and R.W. Prager, "Sensorless reconstruction of unconstrained freehand 3D ultrasound data," *Ultrasound Med. Biol.*, vol. 33, no. 3, pp. 408–419, 2007. DOI: 10.1016/j.ultrasmedbio.2006.09.015. 127

[115] J.C. Seabra, F. Ciompi, O. Pujol, J. Mauri, P. Radeva, and J. Sanches, "Rayleighmixture model for plaque characterization in intravascular ultrasound," *IEEE Biomed. Eng.*, vol. 58, no. 5, pp. 1314–1324, 2001. DOI: 10.1109/TBME.2011.2106498. 127

[116] M.A.H. Khan, "3D reconstruction of ultrasound images," MSc in vision and robotics, University of Burgundy, University of Girona and University of Heriot Watt., 2008. 127

[117] J. Revell, M. Mirmehdi, and D. McNally, "Computer vision elastography:speckle adaptive motion estimation for elastography using ultrasoundsequences," *IEEE Med. Imaging*, vol. 24, no. 6, pp. 755–66, 2005. DOI: 10.1109/TMI.2005.848331. 127

[118] H. Geyer, G. Caracciolo, H. Abe, S. Wilansky, S. Carerj, F. Gentile et al., "Assessment of myocardial mechanics using speckle tracking echocardi-ography: fundamentals and clinical applications," *J. Am. Soc. Echocardiogr.*, vol. 23, no. 4, pp. 351–69, 2010. DOI: 10.1016/j.echo.2010.02.015. 127

[119] M. Alessandrini, PhD thesis, "Statistical methods for analysis and processing of medical ultrasound: applications to segmentation and restoration." Universita di Bologna, 2011. 127

[120] F. Destrempes, G. Soulez, M.-F. Giroux, J. Meunier, and G. Cloutier, "Segmentation of plaques in sequences of ultrasonic B-mode images of carotidarteries based on motion estimation and Nakagami distributions," *IEEE Int. Ultrasonics Symposium (IUS)*, pp. 2480–24833, 2009. DOI: 10.1109/ULTSYM.2009.5441741. 127

[121] N. Paragios and R. Deriche, "Geodesic active contours and level sets for the detection and tracking of moving objects," *IEEE Trans. Pattern. Anal. Mach. Intell.*, vol. 22, no. 3, pp. 266–80, 2000. DOI: 10.1109/34.841758. 127

[122] Y.Y. Boykov and M.-P. Jolly, "Interactive graph cuts for optimal boundary & region segmentation of objects in ND images," *Computer Vision, ICCV 2001. Proc. 8th IEEE Int. Conf.*, pp. 105–112, 2001. DOI: 10.1109/ICCV.2001.937505. 127

[123] M. Oezkan, A. Erdem, M. Sezan, and A. Tekalp, "Effcient multi-frame Wiener restoration of blurred and noisy image sequences," *IEEE Trans. Image Proces.*, vol. 1, pp. 453–476, Oct. 1992. DOI: 10.1109/83.199916. 128

[124] P.M.B. Van Roosmalen, S.J.P. Westen, R.L. Lagendijk, and J. Biemond, "Noise reduction for image sequences using an oriented pyramid threshold technique," *IEEE Int. Conf. Image Proces.*, vol. 1, pp. 375–378, 1996. DOI: 10.1109/ICIP.1996.559511. 128

[125] M. Vetterli, J. Kovacevic, *Wavelets and subband coding,* Prentice Hall, 1995. 128

[126] S. Winkler, *Digital video quality, Vision models and metrics,* John Wiley & Sons, 2005. DOI: 10.1002/9780470024065. 128, 131

[127] J.-H. Jung, K. Hong, and S. Yang, "Noise reduction using variance characteristics in noisy image sequence," *Int. Conf. Consumer Electronics*, pp. 213–214, 8–12 Jan. 2005. DOI: 10.1109/ICCE.2005.1429793. 128

[128] M. Bertalmio, V. Caselles, and A. Pardo, "Movie Denoising by average of warped lines," *IEEE Trans. Image Proces.*, vol. 16, no. 9, pp. 233–2347, 2007. DOI: 10.1109/TIP.2007.901821. 128

[129] B. Alp, P. Haavisto, T. Jarske, K. Oestaemoe, and Y. Neuro, "Median based algorithms for image sequence processing," *SPIE Visual Commun. & Image Proces.*, pp. 122–133, 1990. DOI: 10.1117/12.24175. 128, 131

[130] A. Panayides, M.S. Pattichis, C.S. Pattichis, C.P. Loizou, M. Pantziaris, and A. Pitsillides, "Atherosclerotic plaque ultrasound video encoding, wireless transmission, and quality assessment using H.264," *IEEE Trans. Inform. Tech. Biomed.*, vol. 15, no. 3, pp. 387–397, 2011. DOI: 10.1109/TITB.2011.2105882. 129, 131

[131] T. Painter and A.S. Spanias, "Perceptual Coding of Digital Audio," *Proc. IEEE*, vol. 88, no. 4, pp. 451–513, 2000. DOI: 10.1109/5.842996. 129, 131

[132] A.S. Spanias, *Digital Signal Processing; An Interactive Approach*, 2^{nd} ed., 403 pages, Textbook with JAVA exercises, ISBN 978–1-4675-9892-, Lulu Press On-demand Publishers Morrisville, NC, May 2014.

[133] A.S. Spanias, "Speech Coding: A Tutorial Review," *Proc. IEEE*, pp. 1441–1582, vol. 82, no. 10, 1994. DOI: 10.1109/5.326413.

[134] J. Thiagarajan, K. Ramamurthy, P. Turaga, and A. Spanias, "Image Understanding using sparse representations, in *Synthesis Lectures on Image, Video, and Multimedia Processing*, 978–1627053594, 118 pages, Ed. Al Bovik, 2014. DOI: 10.2200/S00563ED1V01Y201401IVM015. 131

[135] C.P. Loizou and C.S. Pattichis, *Despeckle filtering for ultrasound imaging and video*, Volume II: Selected applicatios, Ed. Morgan & Claypool Publishers, CA, USA, 2015. DOI: 10.2200/S00116ED1V01Y200805ASE001. 132