CERTIFICATE OF ORIGINALITY

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____________________(Signed)

_____Bo Peng_______(Name of student)

Abstract

Image segmentation is a fundamental yet still challenging problem in computer vision and image processing. In this thesis, we address this problem in light of the graph-based theory. An interactive and an automatic segmentation algorithms are proposed to efficiently partition the image into meaningful disjoint regions. For the interactive segmentation algorithm, we present an iterated region merging based graph cuts algorithm which is a novel extension of the standard graph cuts algorithm. Graph cuts addresses segmentation in an optimization framework and finds a globally optimal solution to a wide class of energy functions. However, the extraction of objects in a complex background often requires a lot of user interaction. The proposed algorithm starts from the user labeled sub-graph and works iteratively to label the surrounding un-segmented regions. In each iteration, only the local neighboring regions to the labelled regions are involved in the optimization so that much interference from the far unknown regions can be significantly reduced. Meanwhile, the data models of the object and background are updated iteratively based on high confident labelled regions. The sub-graph requires less user guidance for segmentation and thus better results can be obtained under the same amount of user interaction. The proposed automatic segmentation algorithm is working in a region merging style. With an initially over-segmented image, it is performed by iteratively merging the regions according to a statistical test. There are two essential issues in a region merging algorithm: order of merging and the stopping criterion. These two issues are solved by a novel predicate, which is defined by the sequential probability ratio test (SPRT) and the minimal cost criterion. In addition, a faster algorithm is developed to accelerate the region merging process, which maintains a nearest neighbor graph (NNG) in each iteration.

Moreover, we consider the problem of evaluating the quality of image segmentations, which is an indispensable step for choosing an appropriate output of the image segmentation algorithms. Based on the characteristics of human visual system, we assume that if a segmentation is "good", it can be constructed by some pieces of the ground truth segmentations. Then for a given segmentation, we construct adaptively a new ground truth which can be locally matched to the segmentation as much as possible and preserve the structural consistency in the ground truths. The quality of the segmentation can then be evaluated by measuring its distance to the composite ground truth. We use the structure-based and the boundary-based measures to validate its effectiveness. To the best of our knowledge, this is the first work that provides a framework to adaptively combine multiple ground truths for quantitative segmentation evaluation. Experiments are conducted on the benchmark images from the Berkeley segmentation database (BSDS). The results show that the proposed method can faithfully reflect the perceptual qualities of segmentations.

Keywords: Image segmentation, graph cuts, region merging, energy minimization, segmentation evaluation

List of Publications

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Bibliography

[1] S. Abney. Understanding the yarowsky algorithm. *Computational Linguistics*, 30(3):365–395, 2004.

[2] A. Agarwala, M. Dontcheva, M. Agrawala, S. Drucker, A. Colburn, B. Curless, D. Salesin, and M. Cohen. Interactive digital photomontage. 23(3):294–302, 2004.

[3] S. Alpert, M. Galun, R. Basri, and A. Brandt. Image segmentation by probabilistic bottom-up aggregation and cue integration.". In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition"*, June 2007.

[4] A. A. Amini, T.E. Weymouth, and R.C. Jam. Using dynamic programming for solving variational problems in vision. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 12, 1990.

[5] P. Arbelaez, M. Maire, C. Fowlkes, and J. Malik. From contours to regions: An empirical evaluation. *IEEE Conference on Computer Vision and Pattern Recognition*, pages 2294–2301, 2009.

[6] B. Ayed and A. Mitiche. A region merging prior for variational level set image segmentation. *IEEE Transactions on Image Processing*, 17(12):2301–2311, 2008.

[7] O. Veksler B. Peng. Parameter selection for graph cut based image segmentation. *British Machine Vision conference*, 2008.

[8] R. Bellman. Dynamic programming. In *Princeton University Press*, 1957.

[9] J. Besag. On the statistical analysis of dirty pictures. *Journal of the Royal Statistical Society*, (48):259–302, 1986.

[10] S. Beucher and C. Lantuẽjoul. Use of watersheds in contour detection. *International workshop on image processing, real-time edge and motion detection*, 1979.

[11] M. Bleyer and M. Gelautz. Graph-based surface reconstruction from stereo pairs using image segmentation. *SPIE Signal Processing and Target Recognition*, pages 288–299, 2005.

[12] M. Borsotti, P. Campadelli, and R. Schettini. Quantitative evaluation of color image segmentation results. *Pattern Recognition Letter*, 19(8):741–747, 1998.

[13] Y. Boykov and M.P. Jolly. Interactive graph cuts for optimal boundary and region segmentation. *International Conference on Computer Vision*, 1:105–112, 2001.

[14] Y. Boykov and V. Kolmogorov. Computing geodesics and minimal surfaces via graph cuts. *International Conference on Computer Vision*, 1:26–33, 2003.

[15] Y. Boykov and G. Funka Lea. Graph cuts and efficient n-d image segmentation. *International Journal of Computer Vision*, 69(2):109–131, 2006.

[16] Y. Boykov, O. Veksler, and R. Zabih. Fast approximate energy minimization via graph cuts. *IEEE Transactions on Pattern Analysis and Machine*

Intelligence, 23(11):1222–1239, 2001.

[17] R.W. Buccigrossi and E.P. Simoncelli. Image compression via joint statistical characterization in the wavelet domain. *Image Processing, IEEE Transactions on*, 8(12):1688–1701, 1999.

[18] F. Calderero and F. Marques. General region merging approaches based on information theory statistical measures. *The 15th IEEE International Conference on Image Processing*, pages 3016–3019, 2008.

[19] J. Canny. A computational approach to edge detection. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 8:679–698, 1986.

[20] H.D Cheng and Y. Sun. A hierarchical approach to color image segmentation using homogeneity. *IEEE Transactions on Image Processing*, 9:2071–2082, 2000.

[21] H. Christensen and P. Phillips. Empirical evaluation methods in computer vision. *World Scientific Publishing Company*, 2002.

[22] D. Comanicu and P. Meer. Mean shift: A robust approach toward feature space analysis. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 24:603–619, 2002.

[23] D. Crevier. Image segmentation algorithm development using ground truth image data sets. *Comput. Vis. Image Underst.*, 112:143–159, November 2008.

[24] C. Fowlkes D. Martin and J. Malik. Learning to detect natural image boundaries using local brightness, color and texture cues. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 26(5), 2004.

[25] A. Delong, A. Osokin, H. Isack, and Y. Boykov. Fast approximate energy

minimization with label costs. *In IEEE conference on Computer Vision and Pattern Recognition*, 2010.

[26] F. Marques F. Calderero. Region merging techniques using information theory statistical measures. *IEEE Transactions on Image Processing*, 19:1567–1586, 2010.

[27] A.X. Falcão and F.P.G. Bergo. Interactive volume segmentation with differential image foresting transforms. *IEEE Trans. on Medical Imaging*, 23:1100–1108, 2004.

[28] A.X. Falcão, J. Stolfi, and R.A. Lotufo. Ultrafast user-steered image segmentation paradigm: live-wire-on-the-fly. *IEEE Transactions on Medical Imaging*, 19(1):55–62, 2000.

[29] A.X. Falcão, J. Stolfi, and R.A. Lotufo. The image foresting transform: Theory, algorithms, and applications. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 26:19–29, 2004.

[30] A.X. Falcão, J.K. Udupa, S. Samarasekara, and S. Sharma. User-steered image segmentation paradigms: Live wire and live lane. *Graphical Models and Image Processing*, 60:233–260, 1998.

[31] P. Favaro and S. Soatto. A variational approach to scene reconstruction and image segmentation from motion blur cues. *IEEE Conference on Computer Vision and Pattern Recognition*, pages 631–637, 2004.

[32] P. Felzenszwalb and D. Huttenlocher. Efficient graph-based image segmentation. *International Journal on Computer Vision*, 59(2):167–181, 2004.

[33] M. Fernand. Sequential algorithms for cell segmentation: maximum efficiency? *International symposium on clinical cytometry and histometry, Scholoss*

Elmau, 1986.

[34] M. Fernand. Hierarchies of partitions and morphological segmentation. *IEEE Workshop on scale-space and Morphology in computer vision*, 2001.

[35] D.A. Forsyth and J.Ponce. Computer vision: A modern approach. In *Prentice Hall*, 2002.

[36] E. Fowlkes and C. Mallows. A method for comparing two hierarchical clusterings. *Journal of the American Statistical Association*, 78(383):553–569, 1983.

[37] G. Funka-lea, Y. Boykov, C. Florin, M. Jolly, R. Moreau-gobard, R. Ramaraj, and D. Rinck. Automatic heart isolation for ct coronary visualization using graph-cuts. *In IEEE International Symposium on Biomedical Imaging*, pages 614–617, 2006.

[38] S. Geman and D. Geman. Stochastic relaxation, gibbs distribution and the bayesian restoration of images. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 6(6):721–741, 1984.

[39] S. Geman and C. Graffigne. Markov random field image models and their applications to computer vision. *In A. M. Gleason (Ed.), Proceedings of the International Congress of Mathematicians*, pages 1496–1517, 1987.

[40] S. Geman and D. McClure. Bayesian image analysis: An application to single photon emission tomography. *In Proceedings of the Statistical Computing Section*, pages 12–18, 1985.

[41] R.C. Gonzalez and R.E. Woods. Digital image processing. Addison Wesley, Reading, MA, 1992.

[42] I.E. Gordon. Theories of visual perception. In *First ed. John Wiley and Sons*,

1989.

[43] L. Grady, Y. Sun, and J. Williams. Handbook of mathematical models in computer vision. pages 453–469. Springer, 2006.

[44] G. Haffari and A. Sarkar. Analysis of semi-supervised learning with the yarowsky algorithm. *23rd Conference on Uncertainty in Artificial Intelligence (UAI)*, 2007.

[45] K. Haris, S.N. Estradiadis, N. Maglaveras, and A.K Katsaggelos. Hybrid image segmentation using watersheds and fast region merging. *IEEE Transactions on Image Processing*, 7:1684–1699, 1998.

[46] J. Huang and D. Mumford. Statistics of natural images and models. In *cvpr*, page 1541, 1999.

[47] Q. Huang and B. Dom. Quantitative methods of evaluating image segmentation. *IEEE Intl. Conf. on Image Processing*, pages 53–56, 1995.

[48] J. J. Liu and H.Y. Shum. Paint selection. *ACM Transactions on Graphics*, 2009.

[49] X. Jiang, C. Marti, C. Irniger, and H. Bunke. Distance measures for image segmentation evaluation. *EURASIP Journal on Applied Signal Processing*, 2006:209–209, 2006.

[50] M.P. Jolly, H. Xue, L. Grady, and J. Guehring. Combining registration and minimum surfaces for the segmentation of the left ventricle in cardiac cine mr images. *Proc. of Medical Image Computing and Computer-Assited Intervation*, pages 910–918, 2009.

[51] H. Kang, A.A. Efros, M. Hebert, and T. Kanade. Image composition for object pop-out. In *Computer Vision Workshops (ICCV Workshops), 2009*

IEEE 12th International Conference on, pages 681–688, 2009.

[52] M. Kass, A. Witkin, and D. Terzopoulos. Snakes: Active contour models. *International Journal of Computer Vision*, 2:321–331, 1988.

[53] K. Koffka. Principles of gestalt psychology. In *New York: Harcourt, Brace and World*, 1935.

[54] V. Kolmogorov and Y. Boykov. What metrics can be approximated by geo-cuts, or global optimization of length/area and flux. *International Conference on Computer Vision*, 1:564–571, 2005.

[55] V. Kolmogorov, A. Criminisi, A. Blake, G. Cross, and C. Rother. Bi-layer segmentation of binocular stereo video. *IEEE Conference of Computer Vision and Pattern Recognition*, pages 407–414, 2005.

[56] C. Lam and S. Yuen. An unbiased active contour algorithm for object tracking. *Pattern Recognition Letters*, 19(5-6):491–498, 1998.

[57] S. LaValle and S.M. Hutchinson. Bayesian region merging probability for parametric image models. *Proc. IEEE Computer Soc.Conf. Computer Vision Pattern Recognition*, pages 778–779, 1993.

[58] S. Lee and M.M. Crawford. Unsupervised multistage image classification using hierarchical clustering with a bayesian similarity measure. *IEEE Transactions on Image Processing*, 14:312–320, 2005.

[59] Y. Li, J. Sun, C.K. Tang, and H.Y. Shum. Lazy snapping. *ACM Transactions on Graphics*, 23:303–308, 2004.

[60] H. Liu, Q. Guo, M. Xu, and I. Shen. Fast image segmentation using region merging with a k-nearest neighbor graph. *IEEE Conference on Cybernetics and Intelligent Systems*, pages 179–184, 2008.

[61] J. Liu and Y. H. Yang. Multiresolution color image segmentation. *IEEE Trans. Pattern Anal. Mach. Intell.*, 16:689–700, July 1994.

[62] B. Marcotegui and S. Beucher. Fast implementation of waterfall based on graphs. *Computational Imaging and Vision*, 30:177–186, 2005.

[63] D. Martin. An empirical approach to grouping and segmentation. *Ph.D. dissertation U. C. Berkeley*, 2002.

[64] D. Martin, C. Fowlkes, D. Tal, and J. Malik. A database of human segmented natural images and its application to evaluating segmentation algorithms and measuring ecological statistics. *International Conference on Computer Vision*, 2001.

[65] P.A.V. Miranda and A.X. Falcão. Links between image segmentation based on optimum-path forest and minimum cut in graph. *Journal of Mathematical Imaging and Vision*, 35:128–14, 2009.

[66] P.A.V. Miranda, A.X. Falcão, and J.K. Udupa. Synergistic arc-weight estimation for interactive image segmentation using graphs. *Computer Vision and Image Understanding*, 114:85–99, 2009.

[67] A. Mishra, P. Fieguth, and D. Clausi. Accurate boundary localization using dynamic programming on snakes. *Proceedings of the Canadian Conference on Computer and Robot Vision*, 2008.

[68] A. Moore and S. Prince. “lattice cut” - constructing superpixels using layer constraints. *IEEE Conference on Computer Vision and Pattern Recognition*, pages 2117–2124, 2010.

[69] A. Moore, S. Prince, J. Warrell, U. Mohammed, and G. Jones. Superpixel lattices. *IEEE Conference on Computer Vision and Pattern Recognition*,

pages 1–8, 2008.

[70] A. Moore, S. Prince, J. Warrell, U. Mohammed, and G. Jones. Scene shape priors for superpxiel segmentation. *International Conference on Computer Vision*, pages 771–778, 2009.

[71] F. Moscheni, S. Bhattacharjee, and M. Kunt. Spatio-temporal segmentation based on region merging. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 20:897–915, 1998.

[72] R. Nock and F. Nielsen. Statistical region merging. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 26:1452–1458, 2004.

[73] S. Osher and J.A. Sethian. Fronts propagating with curvature dependent speed: Algorithm based on hamilton jacobi formulations. *Journal of Computational Physics*, 79:12–49, 1988.

[74] S.J Osher and R.P Fedkiw. Level set methods and dynamic implicit surfaces. Springer Verlag, 2002.

[75] O.Veksler. Star shape prior for graph-cut image segmentation. *Proceedings of the 10th European Conference on Computer Vision*, pages 454–467, 2008.

[76] B. Paul, L. Zhang, and X. Wu. Canny edge detection enhancement by scale multiplication. *IEEE. Trans. on Pattern Analysis and Machine Intelligence*, 27:1485–1490, 2005.

[77] V. Zavadsky Y. Boykov P.Das, O.Veksler. Semiautomatic segmentation with compact shape prior. *Image and Vision Computing*, 27.

[78] B. Peng, L. Zhang, and J. Yang. Iterated graph cuts for image segmentation. *Asian Conference on Computer Vision*, 2009.

[79] D.P. Huttenlocher P.F. Felzenszwalb. Image segmentation using local vari-

ations. *Proceedings of IEEE International Conference on Computer Vision and Pattern Recognition*, pages 98–104, 1998.

[80] R. Potts. Some generalized order-disorder transformation. *Proceedings of the Cambridge Philosophical Society*, 48:106–109, 1952.

[81] W. Rand. Objective criteria for the evaluation of clustering methods. *Journal of the American Statistical Association*, 66(336):846–850, 1971.

[82] X. Ren and M. Jitendra. Learning a classification model for segmentation. *IEEE Conference on Computer Vision*, pages 10–17, 2003.

[83] C. Van Rijsbergen. Information retrieval. *second ed. Dept. of Computer Science, Univ. of Glasgow*, 1979.

[84] C. Rother, V. Kolmogorov, and A. Blake. Grabcut-interactive foreground extraction using iterated graph cuts. *ACM Transactions on Graphics*, pages 309–314, 2004.

[85] B. Russell, A. Efros, J. Sivic, W. Freeman, and A. Zisserman. Using multiple segmentations to discover objects and their extent in image collections. *IEEE Conference on Computer Vision and Pattern Recognition*, 2006.

[86] B. Russell, A. Efros, J. Sivic, W.T. Freeman, and A. Zisserman. Segmenting scenes by matching image composites. *Advances in Neural Information Processing Systems*, pages 1580–1588, 2009.

[87] M. Sampat, Z. Wang, S. Gupta, A. Bovik, and M. Markey. Complex wavelet structural similarity: A new image similarity index. *IEEE Transactions on Image Processing*, 18(11):2385–2401, 2009.

[88] K.H. Seo, J.H. Shin, W. Kim, and J.J. Lee. Real-time object tracking and segmentation using adaptive color snake model. *International Journal of*

Control, Automation, and Systems, 4(2):236–246, 2006.

[89] J.A Sethian. Level set methods and fast marching methods. Cambridge University Press, 1999.

[90] J. Shi and J. Malik. Normalized cuts and image segmentation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 22:888–905, 1997.

[91] Y. Shu, G.A, Bilodeau, and F. Cheriet. Segmentation of laparoscopic images: integrating graph-based segmentation and multistage region merging. *The 2nd Canadian Conference on Computer and Robot Vision*, pages 429–436, 2005.

[92] A. Trẽmeau and P. Colantoni. Regions adjacency graph applied to color image segmentation. *IEEE Transactions on Image Processing*, 9:735–744, 2000.

[93] R. Unnikrishnan and M. Hebert. Measures of similarity. *IEEE Workshop on Applications of Computer Vision*, pages 394–400, 2005.

[94] R. Unnikrishnan, C. Pantofaru, and M. Hebert. Toward objective evaluation of image segmentation algorithms. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 29(6):929–944, 2007.

[95] C. Rother V. Kolmogorov, Y. Boykov. Applications of parametric maxflow in computer vision. *IEEE 11th International Conference on Computer Vision*, pages 1–8, 2007.

[96] L. Vincent and P. Soiller. Watersheds in digital spaces: an efficient algorithm based on immersion simulations. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 13(6):583–598, 1991.

[97] P. Viola and W. Wells. Alignment by maximization of mutual information.

3:16–23, 1995.

[98] A. Wald. Sequential analysis. In *Wiley Publications in Statistics*, 1947.

[99] T. Wan, N. Canagarajah, and A. Achim. Statistical multiscale image segmentation via alpha-stable modeling of wavelet coefficients. *IEEE Transactions on Multimedia*, 11:624–633, 2009.

[100] S. Wang and J. M. Siskind. Image segmentation with ratio cut. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 25(6):675–690, 2003.

[101] Z. Wang and A. Bovik. Modern image quality assessment. 2006.

[102] Z. Wang, A. Bovik, H. Sheikh, and E. Simoncelli. Image quality assessment: From error visibility to structural similarity. *IEEE Trans. on Image Process*, 13(4):600–612, 2004.

[103] M. Wertheimer. Laws of organization in perceptual forms (partial translation),a sourcebook of gestalt psycychology. pages 71–88. W.B.Ellis, ed.Harcourt, Brace, 1938.

[104] Z. Wu. Homogeneity testing for unlabeled data: A performance evaluation. 55:370–380, 1993.

[105] Z. Wu and R. Leahy. An optimal graph theoretic approach to data clustering theory and its application to image segmentation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 15(11):1101–1113, 1993.

[106] O. Veksler Y. Boykov and R. Zabih. Markov random fields with effcient approximations. *In IEEE Conference on Computer Vision and Pattern Recognition*, pages 648–655, 1998.

[107] V. Kolmogorov Y. Boykov. An experimental comparison of min-cut/max-flow algorithms for energy minimization in vision. *IEEE transactions on*

Pattern Analysis and Machine Intelligence, 26(9):1124–1137, 2004.

[108] H. Shum Y. Li, J. Sun. Video object cut and paste. *ACM Transactions on Graphics*, 24:595–600, 2005.

[109] W. Chen Q. Peng Y. Zeng, D. Samaras. Topology cuts: A novel min-cut/max-flow algorithm for topology preserving segmentation in n-d images. *Computer Vision and Image Understanding*, 112:81–90, 2008.

[110] D. Yarowsky. Unsupervised word sense disambiguation rivaling supervised methods. *Proceedings of the 33rd Annual Meeting of the Association for Computational Linguistics*, pages 189–196, 1995.

[111] S. Yu, R. Gross, and J. Shi. Concurrent object segmentation and recognition with graph partitioning. *Neural Information Processing Systems*, 2002.

[112] H. Zhang, J. Fritts, and S. Goldman. An entropy-based objective segmentation evaluation method for image segmentation. *SPIE Electronic Imaging Storage and Retrieval Methods and Applications for Multimedia*, pages 38–49, 2004.

[113] L. Zhang and B. Paul. Edge detection by scale multiplication in wavelet domain. *Pattern Recognition Letters*, 23:1771–1784, 2002.