Computer Vision and Image Understanding **77,** 79–83 (2000)
doi:10.1006/cviu.1999.0819, available online at http://www.idealibrary.com on IDEAL®

GUEST EDITORS' INTRODUCTION

Analysis of Volumetric Images

Research in 2-D image analysis has more than 30 years of history and has matured reasonably [1]. Research in volume image analysis, however, is still in its infancy. Three-dimensional scanners that produce volumetric images have been around for some time, and although methods for analyzing and visualizing such images in volume form have been pursued for nearly 25 years [2], brisk activity in this area is a rather recent phenomenon [3].

This special issue is intended to review previous work in volume image analysis and introduce some new results. Research in volume image analysis can be categorized into the following areas.

1. *Preprocessing:* This includes operations that prepare an image for analysis. Such operations are, for instance, filtering to reduce image noise [4] or enhance the edges [5], resampling to produce an isotropic volume from a stack of cross-sectional images [6, 7], and selection of a volume of interest from a large volumetric image [8].

2. *Edge detection:* In volumetric images, edges appear as surfaces and separate regions of different properties from each other. Many 2-D edge detection methods have been extended to three dimensions to detect edges in volumetric images. Laplacian of Gaussian [9], nonmaxima suppression [10], functional fitting [11], and optimization [12] are such examples. In this issue, Brejl and Sonka [13] extend the 2-D edge detector of Haralick and Zuniga [14] to three dimensions to detect edges in anisotropic volume images.

3. *Segmentation:* This is the process of partitioning an image into meaningful regions. In general, image segmentation can be categorized into region-based and edge-based methods. Region-based methods make decisions based on region intensity properties, and edge-based methods use intensity gradients to separate different regions from each other. A large number of 3-D image segmentation methods have been developed [15, 16]. In this issue, López *et al.* [17] describe a method for detecting creases in images. Creases, which measure medialness, appear as surfaces in volumetric images. The proposed method can effectively create surface structures that separate nearby regions of similar properties. Saha *et al.* [18] have extended the definition of fuzzy connectedness to include local object size. The new definition enables use of object scale in computation of the affinity relations used in fuzzy connectedness and has been demonstrated to perform better than the connectedness methods without using scale. Reinhardt *et al.* [19] describe an interactive segmentation method in which the user first interactively segments a number of frames in an image sequence, and

1077-3142/00 $35.00

the program then, by interpolation, estimates and guides the segmentation in other image frames.

4. *Shape modeling:* This includes methods that represent objects obtained as a result of an image segmentation process. In volumetric images, an object can be represented either by a solid or by a surface. Past work on representation of free-form objects has mostly focused on the surface representation, and most significant developments have considered digital surfaces [20], superquadrics [21–23], hyperquadrics [24, 25], and free-form surfaces [26]. In this issue, Lorenz and Krahnstöver [27] introduce a method for creating a shape model that statistically describes variations among a number of given shapes. In addition, Guimond *et al.* [28] describe a method for constructing an average brain model from a number of MR brain images.

5. *Registration:* This is the process of overlaying two images to either combine information from different sensors or compare images obtained with the same sensor at different times. A large number of papers have been published in the area of image registration [29–31]. Mutual information has proven very effective in registration of multimodal images [32], but in this issue Pluim *et al.* [33] point out a problem with determination of registration parameters with subpixel accuracy using the mutual information and demonstrate that patterns of local extrema in the similarity measure between images impede determination of the optimal registration with subpixel accuracy. Alexander and Gee [34] describe a nonlinear method for registering brain images of different individuals. The ability to map normal brain scans to each other makes it possible to determine the distribution of warps between the scans.

6. *Feature selection:* Features describe properties of an image or of a region. They could be statistical [35] or structural [36]. In this issue López *et al.* [17] describe methods for extracting structural features in volumetric images. Such features can be used to characterize and recognize objects.

7. *Recognition:* If statistical features are used, recognition in three dimensions can be dealt with in the same way as in two dimensions. However, if structural features are used, new methods have to be developed for 3-D images. In the past, systems to recognize 3-D objects from their parts [37, 38] and systems to recognize objects represented by superquadrics and deformable models [39] have been developed.

8. *Motion detection and tracking:* Work in this area has mostly used deformable models such as superquadrics. After a model is fitted to data in each image frame, the model is tracked from one frame to the next to determine motion [21, 40, 41]. An alternative approach is to compute the displacement vector field between successive frames, and from the vector field determine motion [42, 43]. Digital surfaces have also been used in tracking motion of rigid bodies, such as the bones at a joint, for understanding their normal and abnormal patterns of motion, and for evaluating joint surgery [44].

9. *Visualization:* Although display of 2-D images is straightforward, display of 3-D images to convey information about an entire volume to the viewer simultaneously is a challenging problem. Considerable effort has gone into developing techniques that render volumetric images [3, 45–47]. Effective visualization of volumetric images is in demand because when automatic methods for reliably analyzing and quantifying image properties are not available, visualization can provide a means for visually analyzing images and quantifying their properties with interactive tools.

The list of references given here is by no means a complete list of published work in volume image analysis. Rather, it is meant to provide a short reading list for individuals who would like to start working in this challenging field.

The number of volumetric images produced annually is expected to increase steadily in the future [48]. Consequently, methods that automatically analyze volumetric images will be in considerable demand. We hope that the papers in this issue motivate and accelerate research in volume image analysis.

This special issue would not have been possible without the help of our expert reviewers: D. Alexander, R. Bajcsy, K. Berkner, M. Brejl, G. Chang, G. E. Christensen, N. Duta, A. Falcao, S. Furuie, J. Gee, D. Goldgof, G. Grevera, W. Higgins, R. Lengagne, T. Lei, B. Lelieveldt, R. Lotufo, V. Magnotta, A. Manduca, A. Mojsilovic, W. Park, P. Saha, C. Steger, K. Toennies, M. Viergever, and A. Yuille. We greatly appreciate their contributions.

REFERENCES

1. A. Rosenfeld, Picture processing by computer, *Comput. Surveys* **1**(3), 1969, 147–176. [Progress in picture processing: 1969–1971, *Computing Surveys* **5**(2), 1973, 81–108; Picture Processing: 1972–1998 has appeared in *Computer Graphics and Image Processing*, then in *Computer Vision Graphics, and Image Processing*, then in *Image Understanding*, and finally in *Computer Vision and Image Understanding* annually.]
2. H. K. Huang and R. S. Ledley, Three-dimensional image construction from in vivo consecutive transverse axial sections, *Comput. Biol. Medicine* **5**, 1975, 165–170.
3. J. Udupa and G. Herman, *3-D Imaging in Medicine*, 2nd ed., CRC Press, Boca Raton, FL, 1999.
4. G. Gerig, O. Kubler, R. Kikinis, and F. Jolesz, Nonlinear anisotropic filtering of MRI data, *IEEE Trans. Med. Imag.* **11**, 1992, 221–232.
5. O. Monga and S. Benayoun, Using partial derivatives of 3-D images to extract typical surface features, *Comput. Vision Image Understand.* **61**, 1995, 171–189.
6. G. Grevera and J. Udupa, Shape-based interpolation of multidimensional grey-level images, *IEEE Trans. Med. Imag.* **15**, 1996, 881–892.
7. A. Goshtasby, D. Turner, and L. Ackerman, Matching of tomographic slices for interpolation, *IEEE Trans. Med. Imag.* **11**, 1992, 507–516.
8. J. Udupa, Interactive segmentation and boundary surface formation for 3-D digital images, *Comput. Graphics Image Process.* **18**, 1982, 213–235.
9. M. Bomans, K.-H. Höhne, U. Tiede, and M. Riemer, 3-D segmentation of MR images of the head for 3-D display, *IEEE Trans. Med. Imag.* **9**, 1990, 177–183.
10. W. Pratt, *Digital Image Processing*, Wiley, New York, 1991.
11. D. G. Morgenthaler and A. Rosenfeld, Multidimensional edge detection by hypersurface fitting, *IEEE Trans. Pattern Anal. Mach. Intell.* **3**(4), 1981, 482–486.
12. S. Zhan and R. Mehrotra, A zero-crossing-based optimal three-dimensional edge detector, *Image Understand.* 1994, 242–253.
13. M. Brejl and M. Sonka, Directional 3-D edge detection in anisotropic data: Detector design and performance assessment, *Comput. Vision Image Understand.* **77**, 84–110.
14. R. Haralick and O. Zuniga, Integrated directional derivative gradient operator, *IEEE Trans. Systems, Man, Cybernet.* **17**, 1987, 508–517.
15. J. Bezdek, L. Hall, and L. Clarke, Review of MR image segmentation techniques using pattern recognition, *Med. Phys.* **20**, 1993, 1033–1048.
16. P. Sahoo, S. Soltani, and A. Wong, A survey of thresholding techniques, *Comput. Vision Graphics Image Process.* **41**, 1988, 233–260.
17. A. M. López, D. Lloret, J. Serrat, and J. J. Villanueva, Multilocal creaseness based on the level set extrinsic curvature, *Comput. Vision Image Understand.* **77**, 111–144.
18. P. K. Saha, J. K. Udupa, and D. Odhner, Scale-based fuzzy connected image segmentation: Theory, algorithms, and validation, *Comput. Vision Image Understand.* **77**, 145–174.
19. J. M. Reinhardt, A. J. Wang, T. P. Weldon, and W. E. Higgins, Cue-based segmentation of 4D cardiac image sequences, *Comput. Vision Image Understand.* **77**, 251–262.

20. J. K. Udupa, Multidimensional digital boundaries, *Graphical Models Image Process.* **50**, 1994, 311–323.

21. D. Terzopoulos and D. Metaxas, Dynamic 3-D models with local and global deformations: Deformable superquadrics, *IEEE Trans. Pattern Anal. Mach. Intell.* **13**(7), 1991, 703–713.

22. A. Pentland, Automatic extraction of deformable part models, *Internat. J. Comput. Vision* **4**, 1990, 107–126.

23. F. Solina and R. Bajcsy, Recovery of parametric models from range images: The case of superquadrics with global deformations, *IEEE Trans. Pattern Anal. Mach. Intell.* **12**(2), 1990, 131–147.

24. A. J. Hanson, Hyperquadrics: Smooth deformable shapes with convex polyhedral bounds, *Comput. Vision Graphics Image Process.* **44**, 1988, 191–210.

25. I. Cohen and L. D. Cohen, A hybrid hyperquadric model for 2-D and 3-D data fitting, *Comput. Vision Image Understand.* **63**, 1996, 527–541.

26. A. Goshtasby, Design and recovery of 2-D and 3-D shapes using rational Gaussian curves and surfaces, *Internat. J. Comput. Vision* **10**(3), 1993, 233–256.

27. C. Lorenz and N. Krahnstöver, Generation of point-based 3D statistical shape models for anatomical objects, *Comput. Vision Image Understand.* **77**, 175–191.

28. A. Guimond, J. Meunier, and J.-P. Thirion, Average brain models: A convergence study, *Comput. Vision Image Understand.* **77**, 192–210.

29. P. A. van den Elsen, E. J. D. Pol, and M. A. Viergever, Medical image matching—A review with classification, *IEEE Eng. Med. Biol.* **12**, 1993, 2–39.

30. J. B. Antoine Maintz and M. A. Viergerver, A survey of medical image registration, *Med. Image Anal.* **2**(1), 1998, 1–36.

31. A. Goshtasby and J. Le Moign (Eds.), *Image Registration*, in Pattern Recognition, Vol. 32, No. 1, 1999.

32. F. Maes, A. Collignon, D. Vandermeulen, G. Marchal, and P. Suetens, Multimodality image registration by maximization of mutual information, *IEEE Trans. Med. Imag.* **16**(2), 1997, 187–198.

33. J. P. W. Pluim, J. B. Antoine Maintz, and M. A. Viergever, Interpolation artefacts in mutual information-based image registration, *Comput. Vision Image Understand.* **77**, 211–232.

34. D. C. Alexander and J. C. Gee, Elastic matching of diffusion tensor images, *Comput. Vision Image Understand.* **77**, 233–250.

35. K. G. A. Gilhuija, M. L. Giger, and U. Bick, Automated feature extraction and classification of breast lesions in MRI, in *Proc. SPIE, 1998*, Vol. 3338, pp. 293–300.

36. J.-P. Thirion and A. Gourdon, Computing the differential characteristics of isointensity surfaces, *Comput. Vision Image Understand.* **61**, 1995, 190–202.

37. I. Biederman, Human image understanding: Recent research and a theory, *Comput. Vision Graphics Image Process.* **32**, 1985, 29–73.

38. S. J. Dickinson, A. P. Pentland, and A. Rosenfeld, From volumes to views: An approach to 3-D object recognition, *Image Understand.* **55**, 1992, 130–154.

39. T. Arbel, P. Whaite, and F. P. Perrie, Recognizing volumetric objects in the presence of uncertainty, in *Internat. Conf. Pattern Recognition, 1994*, Vol. A, pp. 470–476.

40. D. Metaxas and D. Terzopoulos, Shape and non-rigid motion estimation through physics-based synthesis, *IEEE Trans. Pattern Anal. Mach. Intell.* **15**(6), 1993, 580–591.

41. A. Pentland and B. Horowitz, Recovery of non-rigid motion and structure, *IEEE Trans. Pattern Anal. Mach. Intell.* **13**(7), 1991, 730–742.

42. J. S. Duncan, R. L. Owen, L. H. Staib, and P. Anandan, Measurement of non-rigid motion using contour shape descriptors, *Proc. Comput. Vision Pattern Recognition*, 1991, 318–324.

43. I. Cohen, N. Ayache, and P. Sulger, Tracking points on deformable objects using curvature information, in *European Conf. Computer Vision, 1992*, pp. 458–465.

44. J. K. Udupa, B. E. Hirsch, S. Samarasekera, H. Hilstrom, G. Bauer, and B. E. Kneeland, Analysis of in vivo 3D internal kinematics of the joints of the foot, *IEEE Trans. Biomed. Engrg.* **45**, 1998, 1387–1396.

45. P. Cignoni, C. Montani, E. Puppo, and R. Scopigno, Multiresolution representation and visualization of volume data, *IEEE Trans. Visualiz. Comput. Graphics* **3**(4), 1997, 352–369.

46. B. Lichtenbelt, R. Crane, and S. Naqvi, *Introduction to Volume Rendering*, Prentice Hall, New York, 1998.
47. W. Schroeder, K. Martin, and B. Lorensen, *The Visualization Toolkit*, Prentice Hall, New York, 1998.
48. N. Ayache, Medical computer vision, virtual reality and robotics, *Image Vision Comput.* **13**(4), 1995, 295–313.

A. Ardeshir Goshtasby
Milan Sonka
Jayaram Udupa
Guest Editors