

operations distinct [80, 81, 82, 83], in many other approaches recognition and pose calculations are accomplished in a coupled process [84, 85, 86, 48, 38].

A relatively low number of end-to-end recognition systems have been reported, compared to the very large amount of effort on system components. Complete systems can be found in [71, 86, 48, 38, 73, 77]. PRIME is being integrated into an end-to-end recognition system. This includes the novel range segmentation strategy in [67, 69] and a recognition strategy based on graph-matching [87]. Applications in the Active Vision discipline [17, 88, 20, 3] and in geographically-distributed real-time manufacturing are being targeted with this system.

References

- [1] M. M. Trivedi and A. Rosenfeld, "On making computers see," *IEEE Trans. on System, Man, and Cybernetics*, vol. 19, no. 6, pp. 1333–1335, 1989.
- [2] A. Rosenfeld, *Advances in Computers*, vol. 27, ch. Computer Vision. Boston: Academic Press, 1988.
- [3] M. M. Trivedi and C. Chen, *Advances in Computers*, vol. 32, ch. Sensor-Driven Intelligent Robotics, pp. 105–148. Boston: Academic Press, 1988.
- [4] M. M. Trivedi, *Encyclopedia of Science and Technology*, ch. Intelligent Robotic Systems, pp. 226–229. New York: McGraw-Hill, 1994.
- [5] C. Thorpe, M. Hebert, T. Kanade, and S. A. Shafer, "Visiosn and navigation for the carnegie-mellon NAVLAB," *IEEE Trans. on Pattern Anal. Machine Intell.*, pp. 362–373, May 1988.
- [6] C. A. Harlow, M. M. Trivedi, R. W. Conners, and D. Phillips, "Scene analysis of high resolution aerial scenes," *Optical Engineering*, pp. 347–355, March 1986.
- [7] P. H. Eichel, E. J. Delp, K. Koral, and A. J. Buda, "A method for fully automatic definition of coronary arterial edges from cineangiograms," *IEEE Trans. Medical Imaging*, pp. 313–320, December 1988.
- [8] L. S. Hibbard, J. S. McGlone, D. W. Davis, and R. A. Hawkins, "Three dimensional representation and analysis of brain energy metabolism," *Science*, pp. 1641–1646, 1987.
- [9] A. M. Darwish and A. K. Jain, "A rule-based approach for visual pattern inspection," *IEEE Trans. on Pattern Anal. Machine Intell.*, pp. 56–68, January 1988.
- [10] R. Kasturi, S. T. Bow, W. El-Masri, J. Shah, J. R. Gattiker, and U. B. Mokate, "A system for interpretation of line drawings," *IEEE Trans. on Pattern Anal. Machine Intell.*, pp. 978–992, October 1990.
- [11] A. Okazaki, T. Kondo, K. Mori, S. Tsunekawa, and E. Kawamoto, "An automatic circuit diagram reader with loop-structure-based symbol recognition," *IEEE Trans. on Pattern Anal. Machine Intell.*, pp. 331–341, May 1988.
- [12] D. Marr, *Vision*. San Fransico, CA: Freeman, 1982.

- [13] M. Okutomi, G. Medioni, and T. Kanade, "A multiple baseline stereo," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 4, pp. 353–363, 1993.
- [14] S. B. Marapane and M. M. Trivedi, "Region-based stereo analysis for robotic applications," *IEEE Trans. on System, Man, and Cybernetics*, vol. SMC-19, pp. 1447–1464, November 1989.
- [15] S. B. Marapane and M. M. Trivedi, "An active vision system for multi-primitive hierarchical stereo analysis and multi-cue depth extraction," in *Proceedings of the Sensor Fusion for Aerospace Systems Conference.*, (Orlando), SPIE, April 1993.
- [16] S. B. Marapane and M. M. Trivedi, "Multi-primitive hierarchical (MPH) stereo analysis," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 16, pp. 227–240, March 1995.
- [17] S. B. Marapane and M. M. Trivedi, "Experiments in active vision with real and virtual robot heads," *International Journal of Applied Intelligence, Special issue on Sensor Fusion*, vol. 5, pp. 237–250, July 1995.
- [18] R. J. Woodham, "Photometric method for determining surface orientation from multiple images," *Optical Engineering*, pp. 139–144, January/February 1980.
- [19] D. Blostein and N. Ahuja, "Shape from texture: Integrating texture element extraction and surface estimation," *IEEE Trans. on Pattern Anal. Machine Intell.*, pp. 1233–1251, December 1989.
- [20] A. K. Dalmia and M. M. Trivedi, "Real-time depth extraction using image streams acquired by a single camera," *Computer Vision and Image Understanding*, To appear 1995.
- [21] A. K. Dalmia and M. M. Trivedi, "3-d structure extraction from image streams: A review," *IEEE Trans. on Pattern Anal. Machine Intell.*, To appear 1996.
- [22] A. K. Dalmia and M. M. Trivedi, "Integrating depth from motion and binocular stereo approaches," *Machine Vision and Applications*, To appear 1996.
- [23] R. A. Jarvis, "A perspective on range finding techniques for computer vision," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 5, no. 2, pp. 122–139, 1983.
- [24] P. J. Besl, "Active, optical range imaging sensors," *Machine Vision and Applications*, vol. 1, pp. 127–152, 1988.
- [25] G. Stockman and G. Hu, "Sensing 3-d surface patches using a projected grid," in *Proceedings Computer Vision and Pattern Recognition Conf.*, pp. 602–607, 1986.
- [26] M. R. Ward, D. P. Rheume, S. W. Holland, and J. H. Dunseth, "Production plant consight installations," Tech. Rep. GMR-4156, General Motors Research Laboratories, Warren, Michigan, August, 1982.
- [27] H. P. Gadagkar, M. M. Trivedi, and T. N. Lassiter, "Versatile multi-modal system for surface profile measurements using a wrist-mounted laser device," in *Proceedings of the Sensor Fusion V Conference*, (Boston), pp. 466–474, SPIE, Nov. 1992.
- [28] A. M. McIvor and R. J. Valkenburg, "Calibrating a structured light system," Tech. Rep. 362, Industrial Research Limited, February 1995.
- [29] F. W. DePiero and R. L. Kress, "Design and in situ calibration of a structured light sensor," in *Proceedings of Intl. Conf. on Intelligent Robotics and Systems*, (Pittsburgh, PA), pp. 513–518, IEEE/RSJ, August 5-9 1995.
- [30] B. L. Burks, F. W. DePiero, J. C. Rowe, C. B. Selleck, and D. L. Jacoboski, "Final results of the application of a structured light source for surface mapping of the fernald k-65 silos," in *Proceedings of The American Nuclear Society*, (Boston), ANS, June 1992.
- [31] S. Kweon, R. Hoffman, and E. Krotkov, "Experimental characterization of the perceptron laser rangefinder," Tech. Rep. CMU-RI-TR-91-1, The Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, 1991.
- [32] S. W. Holland, L. Rossol, and M. R. Ward, *Computer Vision and Sensor-Based Robotics*. New York: Plenum Press, 1978.

- [33] T. Kanade, A. Gruss, and L. R. Carley, "A very fast VLSI rangefinder," in *Proceedings of the 1991 IEEE Intl. Conf. on Robotics and Automation*, (Sacramento, CA), pp. 1322–1329, IEEE, April 1991.
- [34] F. W. DePiero and R. L. Kress, "Camera calibration in a hazardous environment performed in situ with automated analysis and verification," in *Proceedings of ANS Fifth Topical Meeting on Robotics and Remote Systems*, (Knoxville, TN), ANS, April 1993.
- [35] K. L. Boyer and A. C. Kak, "Color encoded structured light for rapid active ranging," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 9, no. 1, pp. 14–28, 1987.
- [36] Y. Shirai and M. Suwa, "Recognition of polyhedrals with a range finder," in *Proceedings of the 2nd Int. Joint Conf. on Artificial Intell.*, (London), pp. 80–87, Sept. 1971.
- [37] G. Agin and T. Binford, "Computer description of curved objects," in *Proceedings of the 3rd Int. Joint Conf. on Artificial Intell.*, pp. 629–640, 1973.
- [38] M. Oshima and Y. Shirai, "Object recognition using three dimensional information," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 5, no. 4, pp. 353–361, 1983.
- [39] M. Oshima and Y. Shirai, "A scene description method using three dimensional information," *Pattern Recognition*, vol. 11, pp. 9–17, 1984.
- [40] S. Tada, A. Gruss, and T. Kanade, "Cmu very fast range-imaging system," Tech. Rep. CMU-CS-93-179, School of Computer Science, 1993.
- [41] B. L. Burks, F. W. DePiero, J. C. Rowe, C. B. Selleck, D. L. Jacoboski, and R. Markus, "Generation of 3 surface maps in waste storage silos using a structured light source," in *Proceedings of The Space Operations, Applications, and Research Symposium*, (Houston), NASA, 1991.
- [42] M. Minou, *Theoretical and experimental studies on basic relations between real world and pictorial patterns and their generating constraints*. PhD dissertation, Kyoto University, Department of Information Science, Nov. 1982.
- [43] M. D. Altscheuler, B. R. Altscheuler, and J. Tobaoda, "Laser electro-optic system for rapid 3-d topographic mapping of surfaces," *Optical Engineering*, vol. 20, no. 6, pp. 953–961, 1981.
- [44] S. Inokuchi, K. Sato, and F. Matsuda, "Range imaging system for 3-d object recognition," in *Proceedings of the 7th International Conf. on Pattern Recog.*, pp. 806–808, 1984.
- [45] K. K. Yeung and P. D. Lawrence, "A low-cost 3d vision system using space-encoded spot projections," in *Proceedings of The SPIE Conf. on Optics, Illumination and Image Sensing for Machine Vision*, pp. 160–172, SPIE, 1986.
- [46] R. J. Popplestone, C. M. Brown, A. P. Ambler, and G. F. Crawford, "Forming models of plane-and-cylinder faceted bodies from light stripes," in *Proc. 4th Int. Joint Conf. on Artificial Intell.*, pp. 664–668, 1975.
- [47] G. Bickel, G. Hausler, and M. Maul, "Triangulation with expanded range of depth," *Optical Engineering*, vol. 24, no. 6, pp. 975–979, 1985.
- [48] O. D. Faugeras and M. Hebert, "The representation, recognition and locating of 3d shapes from range data," *International Journal of Robotics Research*, vol. 5, no. 3, pp. 27–52, 1986.
- [49] M. Rioux, "Laser range finder based on synchronized scanners," *Applied Optics*, vol. 23, no. 21, pp. 3837–3855, 1984.
- [50] B. K. P. Horn, *Robot Vision*. Cambridge, MA: McGraw-Hill, 1984.
- [51] R. E. Kalman, "A new approach to linear filtering and prediction problems," *Trans ASME J. Basic Eng.*, vol. 83, pp. 35–45, 1960.
- [52] J. A. Borrie, *Stochastic Systems for Engineers: Modeling, Estimation and Control*. New York: Prentice Hall, 1992.

- [53] Y. Bar-Shalom and T. E. Fortmann, *Tracking and Data Association*. New York: Academic Press, 1989.
- [54] G. R. Cooper and C. D. McGillem, *Probabilistic Methods of Signal and System Analysis*. Orlando, FL: Harcourt Brace Jovanovich, 1986.
- [55] A. Isaguirre, P. Pu, and J. Summers, "A new development in camera calibration: Calibrating a pair of mobile cameras," tech. rep., Department of Computer and Information Science, GRASP Laboratory, University of Pennsylvania, Philadelphia, 1985.
- [56] G. H. Golub and C. F. V. Loan, *Matrix Computations*. Baltimore: John Hopkins University Press, 2nd ed., 1989.
- [57] G. Strang, *Linear Algebra and its Applications*. New York: Academic Press, 2nd ed., 1980.
- [58] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes in C*. Cambridge, New York: Cambridge University Press, 1988.
- [59] G.-Q. Wei and S. D. Ma, "Two plane camera calibration: A unified model," tech. rep., National Laboratory of Pattern Recognition, Institute of Automation, Chinese Academy of Sciences, Beijing, 1991.
- [60] S. M. Thayer and M. M. Trivedi, "Residual uncertainty in three-dimensional reconstruction using two-planes calibration and stereo methods," *Pattern Recognition*, vol. 28, no. 7, pp. 1073–1082, 1995.
- [61] I. M. Sobol, *A Primer for the Monte Carlo Method*. Boca Raton: CRC Press, 1994.
- [62] R. Duda and P. Hart, *Pattern Classification and Scene Analysis*. New York: John Wiley and Sons, 1973.
- [63] R. C. Bolles and M. A. Fischler, "A ransac-based approach to model fitting and its application to finding cylinders in range data," in *Proceedings of the 7th International Joint Conf. on Artificial Intelligence*, (Vancouver, B.C., Canada), pp. 637–643, IJCAI, Aug 24-28 1981.
- [64] K. L. Boyer, M. J. Mirza, and G. Ganguly, "The robust sequential estimator: A general approach and its application to surface organization in range data," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 16, no. 10, pp. 987–1001, 1994.
- [65] P. J. Besl and R. C. Jain, "Three-dimensional object recognition," *ACM Computing Surveys*, vol. 17, no. 1, 1985.
- [66] F. W. DePiero and M. M. Trivedi, "The evolution of adaptive techniques for range image segmentation," *Submitted to IEEE Trans. Pattern Analysis and Machine Intelligence*, 1996.
- [67] F. W. DePiero and M. M. Trivedi, "Real-time range image acquisition and segmentation using adaptive kernels and kalman filtering," in *Submitted to Intl. Conf. on Robotics and Automation*, (Minneapolis, MN), IEEE, April 22-28 1996.
- [68] F. W. DePiero and M. M. Trivedi, "A synergistic and real-time approach to range image acquisition and segmentation using a profile-based technique," in *Submitted to Computer Vision and Pattern Recognition*, (San Francisco, CA), IEEE Computer Society, June 18-20 1996.
- [69] F. W. DePiero and M. M. Trivedi, "Range profile tracking (RPT): A profile-based approach for robust and real-time range image segmentation," *Submitted to IEEE Pattern Analysis and Machine Intelligence*.
- [70] B. K. P. Horn, "Extended gaussian image," *Proceedings of IEEE*, vol. 61, no. 3, pp. 1671–1686, 1984.
- [71] R. A. Brooks, "Model-based three-dimensional interpretations of two-dimensional images," *IEEE Trans. on Pattern Anal. Machine Intell.*, pp. 140–150, March 1983.
- [72] W. E. L. Grimson and T. Lozano-Perez, "Model-based recognition and localization from sparse range or tactile data," *International Journal of Robotics Research*, vol. 3, pp. 3–35, Fall 1983.
- [73] R. Bolles and P. Horaud, "3DPO: A three-dimensional part orientation system," *International Journal of Robotics Research*, vol. 5, no. 3, pp. 3–26, 1986.

- [74] P. J. Flynn and A. K. Jain, "Cad-based computer vision: From cad models to relational graphs," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 13, no. 2, pp. 114–132, 1991.
- [75] R. T. Chin and C. R. Dyer, "Model-based recognition in robot vision," *ACM Computing Surveys*, vol. 18, no. 1, pp. 67–108, 1986.
- [76] T. O. Binford, "Survey of model-based image analysis systems," *International Journal of Robotics Research*, pp. 18–64, Spring 1982.
- [77] T.-J. Fan, G. Medioni, and R. Nevatia, "Recognizing 3-d objects using surface descriptions," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 11, no. 11, pp. 1140–1157, 1989.
- [78] R. Nevatia, *Machine Perception*. Englewood Cliffs, NJ: Prentice-Hall, 1982.
- [79] D. H. Ballard and C. M. Brown, *Computer Vision*. Englewood Cliffs, NJ: Prentice-Hall, 1982.
- [80] A. P. Ambler, H. G. Barrow, C. M. Brown, R. M. Burstall, and R. J. Popplestone, "A versatile computer-controlled assembly system," *IJCAI*, pp. 298–307, 1973.
- [81] W.-Y. Kim and A. C. Kak, "3-d object recognition using bipartite matching embedded in discrete relaxation," *IEEE Trans. on Pattern Anal. Machine Intell.*, vol. 13, no. 3, pp. 224–251, 1991.
- [82] M. D. Wheeler and K. Ikeuchi, "Sensor modeling, markov random fields and robust localization for recognizing partially occluded objects," in *Proceedings of The Image Understanding Workshop*, (Wash. D. C.), DARPA, April 1993.
- [83] O. D. Faugeras, *Three-Dimensional Computer Vision, A Geometric Viewpoint*. London: MIT Press, 1993.
- [84] G. Stockman, "Object recognition and localization via pose clustering," *Computer Vision, Graphics and Image Processing*, pp. 361–387, June 1987.
- [85] C. R. Bidlack and M. M. Trivedi, "Geometric model based object recognition and localization robotic manipulation tasks," in *Applications of Artificial Intelligence IX Conf.*, (Orlando), pp. 270–280, SPIE, April 1991.
- [86] C. H. Chen and A. C. Kak, "A robot vision system for recognizing 3-d objects in low-order polynomial time," *IEEE Trans. on System, Man, and Cybernetics*, vol. 19, no. 6, pp. 1535–1563, 1989.
- [87] F. W. DePiero, M. M. Trivedi, and S. Serbin, "Graph matching using a direct classification of node attendance," *Accepted by Pattern Recognition Journal*, 1996.
- [88] H. P. Gadagkar and M. M. Trivedi, "An integrated system for active exploration using contact and non-contact sensors," in *Proceedings of The IEEE IROS '92 Conference*, (Raleigh, NC), IEEE, July 1992.