This document contains copies of reports prepared for the ARPA Image Understanding Workshop. Included are Principal Investigator reports and technical results from both the basic and strategic computing programs within ARPA/ISO sponsored projects and certain technical reports from selected scientists from other organizations.

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency or the United States Government.
"Optical Linear Feature Detection Based on Model Pose," Mark R. Stevens and J. Ross Beveridge, Colorado State University .......................................................... 695

"Interleaving 3D Model Feature Prediction and Matching to Support Multi-Sensor Object Recognition," Mark R. Stevens and J. Ross Beveridge, Colorado State University .......................................................... 699

"A Unified Approach to Moving Object Detection in 2D and 3D Scenes," Michal Irani and P. Anandan, David Sarnoff Research Center .......................................................... 707

"Coregistering 3D Models, Range, and Optical Imagery Using Least-Median Squares Fitting," Anthony N. A. Schwickerath and J. Ross Beveridge, Colorado State University .......................................................... 719

Section IV: Understanding Images of People

"Neural Network-Based Face Detection," Henry A. Rowley, Shumeet Baluja, and Takeo Kanade, Carnegie Mellon University .......................................................... 725

"Tracking Humans in Action: A 3D Model-Based Approach," D. M. Gavrila and L. S. Davis, University of Maryland .......................................................... 737

"Face Verification for Real-Time Applications," Raquel Romano, David Beymer, and Tomaso Poggio, Massachusetts Institute of Technology .......................................................... 747

"Machine Understanding of Human Action," Alex Pentland, Massachusetts Institute of Technology .......................................................... 757

"Towards Automated Structural Analysis of Difficult Face Images," Thang Nguyen and Thomas Huang, University of Illinois .......................................................... 765

"Context-Based Visual Hand Gesture Recognition," Rick Kjeldsen, IBM T. J. Watson Research Center and John R. Kender, Columbia University .......................................................... 771

VOLUME II

Table of Contents ........................................................................................................ iii

Author Index ............................................................................................................ xi

PART III: COMPONENT TECHNOLOGIES

Section V: Sensors

"Telecentric Optics for Computational Vision," Masahiro Watanabe and Shree K. Nayar, Columbia University .......................................................... 781

"A Notebook Logmap Active Vision System," Richard S. Wallace, Lehigh University .......................................................... 787

"Sensing the Virtual World--Work in Progress," Mohamed Dekhil, Jed Marti, and Thomas C. Henderson, University of Utah .......................................................... 793

"Reflectance Modeling for Object Recognition and Detection in Outdoor Scenes," Lawrence B. Wolff, The Johns Hopkins University .......................................................... 799


Section VI: Sensor Geometry/Photogrammetry

"Trilinear Constraints Revisited: Generalized Trilinear Constraints and the Tensor Brightness Constraint," A. Shashua and P. Anandan, David Sarnoff Research Center .......................................................... 815

"Tensorial Transfer: Representation of N > 3 Views of 3D Scenes," Shai Avidan, The Hebrew University and Amnon Shashua, Israel Institute of Technology .......................................................... 821

"Affine Object Representations for Calibration-Free Augmented Reality," Kiriakos N. Kutulakos and James Vallino, University of Rochester .......................................................... 825

"Pose Estimation of Multi-Part Curved Objects," Mourad Zerroug and Ramakant Nevatia, University of Southern California .......................................................... 831
<table>
<thead>
<tr>
<th>Title</th>
<th>Authors and Affiliations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alignment and Tracking using Graphics Hardware</td>
<td>William M. Wells III, MIT AI Laboratory, Harvard Medical School, Brigham and Women's Hospital; Michael Halle, MIT Media Laboratory, Harvard Medical School, Brigham and Women's Hospital; Ron Kikinis, Harvard Medical School, Brigham and Women's Hospital; and Paul Viola, MIT AI Laboratory</td>
</tr>
<tr>
<td>The Integrating Resampler and Efficient Image Warping</td>
<td>Ming-Chao Chiang, Columbia University and Terrance E. Boult, Lehigh University</td>
</tr>
<tr>
<td>Robust Recovery of Camera Rotation from Three Frames</td>
<td>B. Rousso and S. Avidan, The Hebrew University of Jerusalem; A. Shashua, Technion of Haifa, Israel; and S. Peleg, The Hebrew University, visiting David Sarnoff Research Center</td>
</tr>
<tr>
<td>Pose Refinement Using a Parameter Hierarchy</td>
<td>Anthony Hoogs, Lockheed Martin Corporation</td>
</tr>
<tr>
<td>Section VII: Feature Extraction and Representation</td>
<td></td>
</tr>
<tr>
<td>Physics-based segmentation: looking beyond color</td>
<td>Bruce A. Maxwell, Carnegie Mellon University and Stephen A. Shafer, Microsoft Corporation</td>
</tr>
<tr>
<td>Robot Vision: Sketching Natural Scenes</td>
<td>Martin A. Fischler, SRI International</td>
</tr>
<tr>
<td>A Bayesian Approach for the Segmentation of SAR Images Using Dynamically Selected Neighborhoods</td>
<td>Thomas A. Ferryman and Bir Bhanu, University of California, Riverside</td>
</tr>
<tr>
<td>Ordinal Representations of Visual Space</td>
<td>Cornelia Fermüller and Yiannis Aloimonos, University of Maryland</td>
</tr>
<tr>
<td>Parallel Implementations of Perceptual Grouping Tasks on Distributed Memory Machines</td>
<td>Cho-Li Wang, Viktor K. Prasanna, and Yongwha Chung, University of Southern California</td>
</tr>
<tr>
<td>Generic, Model-Based Estimation and Detection of Peaks in Image Surfaces</td>
<td>By-Her Wang and Thomas O. Binford, Stanford University</td>
</tr>
<tr>
<td>Detection, Estimation, and Aggregation of Three Major Types of Discontinuities in Image Surfaces</td>
<td>Sheng-Jyh Wang and Thomas O. Binford, Stanford University</td>
</tr>
<tr>
<td>Coalescing Texture Descriptors</td>
<td>Yossi Rubner and Carlo Tomasi, Stanford University</td>
</tr>
<tr>
<td>Segmentation of Multidimensional Images</td>
<td>P. Bajcsy and N. Ahuja, University of Illinois</td>
</tr>
<tr>
<td>Robust Thermophysics-Based Interpretation of Radiometrically Uncalibrated IR Images for ATR and Site Change Detection</td>
<td>D. G. Arnold, USAF Wright Laboratory and University of Virginia; J. Michel, N. Nandakumar, and G. Tsihrintzis, University of Virginia; and V. Velten, USAF Wright Laboratory</td>
</tr>
<tr>
<td>Multiscale Region Detection</td>
<td>Narendra Ahuja and Scott A. Jackson, University of Illinois</td>
</tr>
<tr>
<td>Curvature-Based Signatures for Object Description and Recognition</td>
<td>Elli Angelopoulou, James P. Williams, and Lawrence B. Wolff, Johns Hopkins University</td>
</tr>
<tr>
<td>Detection Performance Methodology</td>
<td>Robert M. Haralick, University of Washington</td>
</tr>
<tr>
<td>Section VIII: Shape Reconstruction</td>
<td></td>
</tr>
<tr>
<td>Constructing High-Precision Geometric Models from Sensed Position Data</td>
<td>William B. Thompson, H. James de St. Germain, Thomas C. Henderson, and Jonathan C. Owen, University of Utah</td>
</tr>
<tr>
<td>Flat Surface Reconstruction Using Minimal Sonar Readings</td>
<td>Thomas C. Henderson, Mohamed Dekhil, Beat Brüderlin, Larry Schenkat, and Larkin Veigel, University of Utah</td>
</tr>
<tr>
<td>Curvature-Based Signatures for Object Description and Recognition</td>
<td>Elli Angelopoulou, James P. Williams, and Lawrence B. Wolff, Johns Hopkins University</td>
</tr>
<tr>
<td>A computational theory of canonical views</td>
<td>Daphna Weinshall and Michael Werman, The Hebrew University of Jerusalem</td>
</tr>
<tr>
<td>3D Reconstruction Based on Homography Mapping</td>
<td>Zhongfei Zhang, State University of New York and Allen R. Hanson, University of Massachusetts, Amherst</td>
</tr>
<tr>
<td>A Multi-Body Factorization Method for Motion Analysis</td>
<td>João Costeira and Takeo Kanade, Carnegie Mellon University</td>
</tr>
</tbody>
</table>
"Deformable Surface Reconstruction Coupled with Discontinuity Edge Detection," Song Han and Gérard Medioni, University of Southern California ............................... 1027

"Surface Approximation and Segmentation of Objects with Unknown Topology," Chia-Wei Liao and Gérard Medioni, University of Southern California ........................................... 1033

"Inference of Surfaces, 3-D Curves, and Junctions from Sparse 3-D Data," Gideon Guy and Gérard Medioni, University of Southern California ........................................... 1041

"Structure and Motion from a Sparse Set of Views," Mi-Suen Lee and Gérard Medioni, University of Southern California ........................................... 1051

"Inference of Segmented, Volumetric Shape from Intensity Images," Parag Havaldar and Gérard Medioni, University of Southern California ........................................... 1057

"Shape Description of Curved 3-D Objects for Aerial Surveillance," Kashi Rao, Texas Instruments ........................................... 1065

"Consistent Site Modeling: Imposing Hard Constraints on Deformable Models," P. Fua, SRI International and C. Brechbühler, Communication Technology Lab, ETH-Zürich ........................................... 1077

"Shape from Appearance: A Statistical Approach to Surface Shape Estimation," Darrell R. Hougen and Narendra Ahuja, University of Illinois ........................................... 1095

"On 3D Shape Synthesis," Heung-yeung Shum, Martial Hebert, and Katsushi Ikeuchi, Carnegie Mellon University ........................................... 1103

"Performance Evaluation and Analysis of Vanishing Point Detection Techniques," Jefferey A. Shufelt, CMU Digital Mapping Laboratory ........................................... 1113

"Resolution and Accuracy of Stereo, Focus, and Shading Methods," Darrell R. Hougen, and Narendra Ahuja, University of Illinois ........................................... 1133

"Shape from Darkness Under Error," David Yang and John R. Kender, Columbia University ........................................... 1141

"Geometric Analysis of Volume Images of the Bronchial and Vascular Trees," Chandrasekhar Pisupati, James P. Williams, and Lawrence B. Wolff, Johns Hopkins University ........................................... 1149

Section IX: Matching and Indexing

"Determining the Similarity of Geometric Models," William B. Thompson, Richard F. Riesenfeld, and Jonathan C. Owen, University of Utah ........................................... 1157


"Recognition by Matching With Edge Location and Orientation," Clark F. Olson and Daniel P. Huttenlocher, Cornell University; and David M. Doria, Hughes Aircraft Company ........................................... 1167

"Determining the Probability of a False Positive When Matching Chains of Oriented Pixels," Clark F. Olson and Daniel P. Huttenlocher, Cornell University ........................................... 1175

"Approximate Hausdorff Matching Using Eigenspaces," Daniel P. Huttenlocher, Ryan H. Lilien and Clark F. Olson, Cornell University ........................................... 1181

"A Scale Space Based Deformable Template Matching Algorithm," Richard J. Qian and Thomas S. Huang, University of Illinois ........................................... 1187

"Complexity of Indexing: Efficient and Learnable Large Database Indexing," Michael Werman and Daphna Weinshall, The Hebrew University of Jerusalem ........................................... 1193

"Scale-Space Matching and Image Retrieval," S. Ravela, R. Mannatha and E. M. Riseman, University of Massachusetts, Amherst ........................................... 1199

"Shape-Based Illustration Indexing and Retrieval: Some First Steps," Scott D. Cohen and Leonidas J. Guibas, Stanford University ........................................... 1209

"A Space-Sweep Approach to True Multi-Image Matching," Robert T. Collins, University of Massachusetts, Amherst ........................................... 1213

Section X: Recognition

"Real-Time 100 Object Recognition System," Shree K. Nayar, Sameer A. Nene, and Hiroshi Murase, Columbia University ........................................... 1223
"Automatic Model Construction for Object Recognition using Inverse Synthetic Aperture Radar Images," Shujun Zhang and Bir Bhanu, University of California, Riverside ........................................ 1229

"Recognition of Articulated Objects in SAR Images," Bir Bhanu, Grinnell Jones, Joon Ahn, Ming Li, and June Yi, University of California, Riverside ......................................................... 1237

"Model-Based Recognition of 3D Curves from One View," Isaac Weiss, University of Maryland .................. 1251

"Recognizing Blasting Caps in X-Ray Images," M. A. Maloof, George Mason University; Z. Duric, George Mason University and University of Maryland; R. S. Michalski, George Mason University; and A. Rosenfeld, University of Maryland .......................................................... 1257

"Model-Based SAR ATR System," Katsushi Ikeuchi, M. D. Wheeler, Taku Yamazaki, and Takeshi Shakunaga, Carnegie Mellon University ...................................................... 1263


"Towards a Theory of Direct Perception," Cornelia Fermüller and Yiannis Aloimonos, University of Maryland .......................................................... 1287

"A Polarization Phase-Based Method for Material Classification and Object Recognition in Computer Vision," Hua Chen and Lawrence B. Wolff, Johns Hopkins University ...................................... 1297

"Memory-Based Recognition for 3-D Objects," Randal C. Nelson, University of Rochester .......................... 1305

Section XI: Visual Control

"Merging Constraints to Plan Camera Positions and Parameters," Steven Abrams and Peter K. Allen, Columbia University; and Konstantinos A. Tarabanis, IBM T. J. Watson Research Center ........................................ 1313

"Decision-Theoretic Cooperative Sensor Planning," Diane J. Cook, Piotr Gmytrasiewicz and Lawrence B. Holder, University of Texas, Arlington ........................................ 1321

"Transparent Grippers: Seeing While Grasping," Anton Nikolaev and Shree K. Nayar, Columbia University ........................................ 1333

"Obstacle avoidance via depth from focus," Illiah R. Nourbakhsh, David Andre, Carlo Tomasi, and Michael R. Genesereth, Stanford University ..................................................... 1339

"Tracking Object Motion Across Aspect Changes for Augmented Reality," S. Ravela, B. Draper, J. Lim, and R. Weiss, University of Massachusetts, Amherst .............................................................. 1345


"Model-Based Gaze Control," Ulf M. Cahn von Seelen and Ruzena Bajcsy, University of Pennsylvania ... 1361

"Vision-Based Neural Network Road and Intersection Detection and Traversal," Todd M. Jochem, Dean A. Pomerleau, and Charles E. Thorpe, Carnegie Mellon University ...................................... 1365

Section XII: Learning in Vision


"Performance Improvement by Input Adaptation Using Modified Hebbian Learning," Yong-Jian Zheng and Bir Bhanu, University of California, Riverside ........................................ 1381

"Reinforcement Learning for Integrating Context with Clutter Models for Target Detection," Songnian Rong and Bir Bhanu, University of California, Riverside ........................................ 1389

"Supervised learning of detection and classification tasks with uncertain training data," Clay Spence, David Sarnoff Research Center ........................................................................ 1395

"Probabilistic Learning of Three-Dimensional Object Models," Gregory Provan and Pat Langley, Institute for the Study of Learning and Expertise; and Thomas O. Binford, Stanford University ........................................ 1403

"Delayed Reinforcement Learning for Closed-Loop Object Recognition," Jing Peng and Bir Bhanu, University of California, Riverside ................................................................. 1429

"Learning an Object's Function by Observing the Object in Action," Zoran Duric, University of Maryland and George Mason University; Ehud Rivlin, University of Maryland and Israel Institute of Technology; and Azriel Rosenfeld, University of Maryland ................................................................. 1437

"Learning Grouping Strategies for 2D and 3D Object Recognition," Bruce A. Draper, University of Massachusetts, Amherst ................................................................. 1447

"Color Channel Mixing in Learning from Appearance," Nadesan Narenthiran and Terrance E. Boult, Lehigh University ................................................................. 1455

Section XIII: IU Systems and System Development


"Parallel Algorithms for Linear Approximation on Distributed Memory Machines," Yongwha Chung, Viktor K. Prasanna, and Cho-Li Wang, University of Southern California ................................................................. 1465

"The MIST Methodology and Its Application to Natural Scene Interpretation," R. S. Michalski, Q. Zhang, M. A. Maloof, and E. Bloedorn, George Mason University ................................................................. 1473

"Solving Diverse Image Understanding Problems Using the Image Understanding Environment," John Dolan, Charles Kohl, Richard Lerner, Amerinex Artificial Intelligence, Inc.; Joseph Mundy, GE Corporate Research and Development; Terrance Boult, Lehigh University; and J. Ross Beveridge, Colorado State University ................................................................. 1481

"SUCCESSOR: Interpretation Overview and Constraint System," Wallace B. Mann and Thomas O. Binford, Stanford University ................................................................. 1505

"Persistent Data Management for Visual Applications," Gokhan Kutlu, Bruce A. Draper, J. Eliot B. Moss, Edward M. Riseman, and Allen R. Hanson, University of Massachusetts, Amherst ................................................................. 1519

"Knowledge-Based Integration of IU Algorithms," C. Shekhar, S. Kuttikkad, and R. Chellappa, University of Maryland ................................................................. 1525

"Statistical Validation of Computer Vision Software," Xufei Liu, Tapas Kanungo, and R. M. Haralick, University of Washington ................................................................. 1533