REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1, 2001	Final Report: Dec ~~01~~, 1993- Jan 31, 2000

4. TITLE AND SUBTITLE
Basic Research in Computer Science: Image Understanding

5. FUNDING NUMBERS
DAA H04-94-G-0006

6. AUTHOR(S)
Takeo Kanade, Steven Shafer, Katsushi Ikeuchi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Computer Science Department
Carnegie Mellon University
Pittsburgh, PA 15213-3890

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
32567.38-C1

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The CMU Image Understanding program performed basic research and technology development toward robust, flexible, and precise vision systems to impact a wide variety of military and civilian applications. The accomplished results include: hypergeometric filter-based image matching; multi-body factorization for structure from motion; a trainable face detection system; 3D surface representation from multiple range images; learning of an object appearance model: recognition of 3D objects in range images by the Spin Image method; eigen window method for SAR image recognition; and shape matching technique and its medical application.

14. SUBJECT TERMS
Image Understanding, Structure from Motion, Model-based Vision, Calibration, Stereo, Factorization, Learning in Vision, Surface Representation, Face Detection

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Final Progress Report

Table of Contents

Statement of the Problem Studied

The CMU Image Understanding program performs basic research and technology development toward robust, flexible, and precise vision systems to impact a wide variety of military and civilian applications. Our areas of focus include: model-based vision, in which objects are recognized from prior or acquired solid models; 3D shape inference, in which image physics are used to infer 3D depth from one or more images; and vision applications including mobile robots, robot sensor calibration, and human-computer interaction.

Most current methods for computer vision still depend, for their low-level analysis, on traditional signal-processing methods such as edge detection and pixel clustering. In contrast, our research on physical models for computer vision addresses modeling physical processes, such as laws of reflection, image formation, and object and sensor properties. These explicit models can cope with highlights, shadows, surface texture, and other phenomena that cause complex variations in intensity and color.

Current vision algorithms are designed as static systems; they use preprogrammed structures and parameters even after recognition and processing failures due to environmental variations and discrepancies between models and reality. Our research aims to develop learning techniques that can overcome such discrepancies and adapt to new environments. These learning algorithms are developed and tested in task-oriented vision problems rather than on a traditional abstract machine-learning problem. Such task-oriented problems include: learning appearance models for virtual reality systems, learning the concept of human faces from examples, learning land-mark models for outdoor navigation, learning the SAR recognition program from examples, and learning what to do by observing human actions.

Summary of the Most Important Results

Hypergeometric filter-based image matching

A hypergeometric filter-based approach has been developed for general image matching problems. Not only is it applicable to a wide range of matching problems such as focus, stereo, optical flow, and affine matching; we can achieve much higher precision using this approach than traditional approaches because window and foreshortening effects are eliminated. In this approach, the effects of the finite window size can be expressed as high order terms in a Taylor expansion. Ignoring those window effects in traditional approaches is equivalent to truncating the Taylor expansion after the first term. Therefore, by truncating the expansion at a higher order, we are able to reduce, and numerically eliminate, window effects. Furthermore, the shift variance effects caused by non-zero gradients of matching parameters such as foreshortening in stereo and affine deformation in optical flow, can be represented analytically as a linear combination of filter outputs. The hypergeometric filter achieves very high precision by taking both window and shift variance effects into consideration. Using the hypergeometric filter approach, we experimented with image matching problems such as depth from defocus with and without slope estimation, depth from stereo with and without foreshortening estimation, optical flow, and affine matching. In all those experiments, our new approach produced higher precision results than those state-of-art techniques designed specifically for individual problems.

Multi-body Factorization for Structure from Motion:

Structure from motion (SFM) has been one of the most active research areas in computer vision during the past two decades. Most of the SFM methods, however, neglect the study of a multi-body problem. Rather, they are based on the assumption that only a single motion is included in the image sequence; either the environment is static and the observer moves, or the observer is static and only one object in the scene is in motion. More difficult and less studied is the general case of an unknown number of objects moving independently. At CMU we have developed the factorization method for robust structure from motion: the initial orthographic factorization, the para-perspective factorization, and the sequential factorization. Yet, all of these methods, as well as other previous methods, can deal with only a single-body problem.

We have developed a new method for separating and recovering the motion and shape of multiple, independently moving objects in a sequence of images. This new method does not require any grouping of features into an object at the image level; nor does it require prior knowledge of the number of objects. The key idea was the introduction of a mathematical construct of object shapes, called the shape interaction matrix, which is invariant to both the object motions and the selection of coordinate systems. This invariant structure is computable solely from the observed trajectories of image features without grouping them into individual objects. Once the matrix is computed, it allows for segmenting features into objects, as well as for recovering the shape and motion of each object by the process of transforming it into a canonical form. The method has been tested successfully with simulated data and simple real image sequences. This method remains to be the only non-heuristic method for the multi-body structure from motion problem.

Trainable face detection

We developed a trainable face detection system that can locate all upright, frontal faces in a scene. The faces can be of any size and can appear against arbitrary backgrounds. The system uses color and motion cues to restrict its search, and can process a 320x240 pixel image in less than a second on an SGI Indy workstation and later in more than 5 frames per second on Pentium II PCs. The system has been used in many application systems within CMU and outside of CMU, including image retrieval and news-on-demand system for quick access to video information, human-computer interaction systems.

3D Surface Representation from Multiple Range Images

For acquiring surface representation, we developed a system that creates 3D surface representations from range images of the object. The method consists of acquiring several range-image views of the object, aligning the image data, merging the image data using the aid of a volumetric representation, and then extracting a triangle mesh from the volumetric representation of the merged data. Our main contribution is a new algorithm, the consensus-surface algorithm, which eliminates many of the troublesome effects of noise and extraneous surface observations in the data. It does so by searching for a consensus of surface observations in order to estimate the implicit distance from each point in the volume to the closest point on the surface. This algorithm can produce accurate object models despite the poor quality of data available from real imagery (for both range and intensity images).

Learning of Object Appearance Model

Generating realistic images of a three dimensional object for virtual reality systems requires two pieces of information: the object's shape (geometric information) and reflectance properties (photometric information) such as color and specularity. While significant progress has been made in computer graphics hardware and image rendering algorithms, object models are still created manually -- a bottleneck for realistic image synthesis.

We have developed a novel approach to learn photometric information as well as geometric information of an object by simply observing a real object. This method not only skips the time-consuming manual modeling, but also provides a much more realistic and accurate appearance of an object when generated by the virtual reality system. The method utilizes a series of color images of an object under a moving light source. Then, it observes the color transition at each pixel, and records it into the four dimensional RGB-Time space, referred to as the temporal-color space. The color transition curve in the temporal-color space can be decomposed into diffuse and specular component curves using the singular value decomposition method. Due to the dichromatic theory, those two curves exist on two hyper-planes in the temporal-color space. By analyzing those two curves, such as width and height on the two hyperplane, the method acquires geometric and photometric information of an object.

Recognition of 3D Objects in Range Images by the Spin Image Method

We have developed a representation that combines the descriptiveness of global object properties with the robustness to partial views and clutter of local shape descriptions. A local basis is computed at an oriented point (3-D point with surface normal) on the surface of an object. All the positions on the object surface now can be described with respect to the basis of other points by two parameters. By accumulating these parameters in a 2-D array, a descriptive image (spin-image) associated with the point is created. Because spin-images describes the coordinates of points on the surface of an object with respect to the local basis, they are local encoding of the global shape of the object and are invariant to rigid transformations.

At recognition time, spin-images from points on the model are compared with spin-images from points in the scene; when two images are similar enough, a point correspondence between model and scene is established. After point matching, a model is localized in the scene by grouping correspondences to compute a transformation, which is subsequently refined, and verified using a modified iterative closest point registration algorithm.

This recognition algorithm has been integrated into a semi-automatic world modeling system called Artisan. Artisan combines 3-D sensors, object modeling and analysis software, and an operator interface to create a 3-D model of a robot's work area. Through object recognition, Artisan assigns semantic meaning to objects in the scene, which facilitates execution of robotic commands and drastically simplifies operator interaction. Artisan was demonstrated in several tasks at the Oakridge National Labs, using a remotely operated mobile platform.

Object Recognition in SAR Images

Automatic target recognition (ATR) using synthetic aperture radar (SAR) images is an important military application area. SAR sensors allow continuous day/night coverage under all weather conditions, and can achieve high spatial resolution even from orbital platforms.

We developed a trainable SAR ATR system based on a new technique "eigenwindows". This system divides each training image into small subwindows, all of which are stored as points in the eigen space. An unknown target image is also broken into subwindows and projected to the eigen space. Each pairing of a target eigenwindow point and a training point votes for a particular target and viewing angle, and the final classification is achieved as the consensus of all such votes. This eigenwindow approach has a number of benefits. First, when some parts of a target are occluded, remaining windows covering visible parts can identify the target. Second, to detect a target with articulated components, we can define separate windows for each, and recognition can proceed separately on the articulated parts and the body. Third, the method is by definition insensitive to image translation. Finally, using multiple small windows rather than a whole image greatly reduces the dimensionality of the eigen spaces that must be manipulated.

The eigenwindow-based SAR ATR system was evaluated it using seven targets types: BMP, BTR60, KTANK, M35, M113, M60 and SCUD. Training images for each target were generated via the XPATCH simulator by varying the azimuth angle from 0 to 359 degrees in 1 degree increments, while maintaining a constant SAR depression angle of 22.5 degrees and resolution of 30 cm/pixel. Test images were also generated via XPATCH, at fractional azimuth values. A target classification produced by the system was considered to be correct if it was of the correct object type, and had an estimated azimuth angle within 5 degrees of the correct angle. Under this criteria, when the system was tasked to produce a single, best candidate hypothesis, the mean classification accuracy was 95% (std of 4%) for unoccluded targets, and 93% (std 5%) for targets occluded up to 50% in the worst case.

Shape Matching Technique and its Medical Application

A shape matching (or registration) method based on the iterative closest point algorithm has been developed and applied to computer-assisted surgical systems. The registration process is a fundamental component of most computer-assisted surgical systems. Registration estimates a spatial transformation between two coordinate systems: a pre-operative system used to construct plans or simulations based upon medical data (e.g., CT, MRI, or X-ray images), and an intra-operative system in which the surgical procedure is performed (e.g., relative to a robot, navigational guidance system, etc.).

This work addresses the problem of improving shape-based registration accuracy via intelligent selection of registration data and on-line estimation of accuracy. Intelligent data selection (IDS) is comprised of geometric constraint analysis, which provides a sensitivity measure shown to be well correlated with registration accuracy; and geometric constraint synthesis, an optimization process, which generates data configurations, which maximize the sensitivity measure for a fixed quantity of data. IDS use the pre-operative shape representation to generate a data collection plan (DCP), which can be used during surgery to guide the acquisition of registration data. On-line accuracy estimation provides an upper bound on true registration accuracy based upon a conventional root-mean-squared error.

After in-vitro on cadaveric specimens and via simulation studies, the above method has been incorporated into the HipNav system, a clinical image-guided orthopedic surgical system, which has been used for more than 100 actual surgeries.

Handling Indeterminacy and Uncertainty in Computer Vision

Parameter indeterminacies are inherent in 3D computer vision. However, there has not been a general and convenient method available for representing and analyzing the indeterminacies and their effects on accuracy. Consequently, up to the present their effects are usually ignored in uncertainty modeling research. We developed gauge-based uncertainty representation for 3D estimation that includes indeterminacies. We represent indeterminacies with orbits in the parameter space and model local linearized parameter indeterminacies as gauge freedoms. Combining this formalism with first order perturbation theory, we are able to model uncertainties along with parameter indeterminacies.

The key to our work is a geometric interpretation of the parameters and gauge freedoms. We solve the problem of how to compare parameter uncertainties despite indeterminacies and added constraints. This permits us to extend the Cramer-Rao lower bound to problems that include parameter indeterminacies. In 3D computer vision the basic quantities that often cannot be recovered include scale, rotation and translation. We use our method to analyze the local effects of these indeterminacies on the estimated shape, and find all the local gauge freedoms. This enables us to express the uncertainties when additional information is available from measurements that constrain the gauge freedoms. Through analytical and empirical means we gain intuition into the effects of constraining the gauge freedoms, for both general Structure from Motion and stereo shape estimation. We include, in our uncertainty model, measurement errors and feature localization errors. These results along with our theory allow us to find optimal constraints on the gauge freedoms that maximize the accuracy of the part of the object we seek to estimate.

List of PUBLICATIONS

(a) Papers Published in Peer-Reviewed Journals

T. Kanade and D.D. Morris, "Factorization Methods for Structure From Motion", Philosophical Transactions of the Royal Society of London, Series A, Vol. 356, No. 1740, pp. 1153-1173, 2001

L. Zitnick and T. Kanade, "A cooperative algorithm for stereo matching and occlusion detection", IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 22, No. 7, July 2000, pp. 675 - 684.

S. Satoh, Y. Nakamura, and T. Kanade, "Name-It: naming and detecting faces in news videos", IEEE Multimedia, Vol. 6, No. 1, January 1999, pp. 22 - 35.

T. Sato and Takeo Kanade, "Contents Extraction from News Video Character Recognition and Associating of Multimodal Information," Information Processing Society of Japan Journal, Vol. 40, No.12, pp.4266-4276, 1999.

Toshio Sato, Takeo Kanade, Ellen K. Hughes, Michael A. Smith and Shin'ichi Satoh, "Video OCR: indexing digital news libraries by recognition of superimposed captions," ACM Multimedia Systems, Vol. 7. pp. 385-395, 1999.

M. Chen, T. Kanade, D. Pomerleau, and H. Rowley, "Anomaly detection through registration," Pattern Recognition, 32, pp.113-128, 1999.

A. Johnson and M. Hebert , "Using spin images for efficient object recognition in cluttered 3D scenes," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 21, No. 5, May, 1999, pp. 433 - 449.

N. Chiba and T. Kanade, "A Tracker for Broker and Closely-Spaced Lines," (in Japanese), Transactions of the Institute of Electronics, Information and Communication Engineers of Japan, Trans. D-II, Vol. J81-D-II, No. 8, pp.1744-1751, August 1998.

M. Uenohara and T. Kanade, "Optimal Approximation of Uniformly Rotated Images: Relationship Between Karhunen-Loeve Expansion and Discrete Cosine Transform," IEEE Transaction on Image Processing, Vol. 7, No. 1, January 1998.

H. Rowley, S. Baluja and T. Kanade, "Neural Network-Based Face Detection," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 20, No. 1, pp.23-38, January 1998.

P. Rander, P.J. Narayanan, T. Kanade, "Virtualized Reality: Constructing Virtual Worlds from Real Scenes," IEEE Multimedia, Immersive Telepresence, Vol. 4, No. 1, pp. 34-47, Jan/Mar 1997.

Toshihiko Morita and Takeo Kanade, "A Sequential Factorization Method for Recovering Shape and Motion From Image Streams," IEEE Trans. on Pattern and Analysis and Machine Intelligence, Vol. 19, No. 8, August, 1997.

Yalin Xiong and Steven A. Shafer, "Moment and Hypergeometric Filters for High Precision Computation of Focus, Stereo and Optical Flow," International Journal of Computer Vision, Vol. 22, No. 1, pp. 25-59, Feb/Mar 1997.

Long Quan and Takeo Kanade, "Affine Structure from Line Correspondences With Uncalibrated Affine Cameras," IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol. 19, No. 9, pp.834-845, August, 1997.

M. Uenohara and T. Kanade, "Use of the Fourier and Karhunen-Loeve Decomposition for Fast Pattern Matching With a Large Set of Templates," IEEE Trans. Pattern Analysis and Machine Intelligence (PAMI), Volume 19, No. 8, pp. 891-898, August 1997.

T. Morita and T. Kanade, "A Sequential Factorization Method for Recovering Shape and Motion from Image Streams," IEEE Trans. Pattern Analysis and Machine Intelligence (PAMI), Volume 19, No. 8, pp. 858-867, August 1997.

H. Shum, M. Hebert, K. Ikeuchi, and R. Reddy, "An integral approach to free-form object modeling," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 19, No. 12, December, 1997, pp. 1366 – 1370.

Y. Sato, I. Sato, and K. Ikeuchi, "Object shape morphing with intermediate reflectance properties," International Journal of Shape Modeling, Vol. 3, No. 1 & 2, pp. 91 – 106, 1997.

T. Kanade, "Immersion into Visual Media: New Applications of Image Understanding," IEEE Expert Intelligent Systems and Their Applications, Vol. 11, No. 1, IEEE Computer Society, pp. 73-80, 1996.

Y. Sato and K. Ikeuchi, "Reflectance analysis for 3D computer graphics model generation," CVGIP Graphical Models and Image Processing, Vol. 58, No. 5, September, 1996, pp. 437 - 451.

H. A. Rowley, S. Baluja and T. Kanade, "Human face detection in visual scenes," in Advances in neural information processing system 8, MIT Press, 1996.

K. Kemmotsu and T. Kanade, "Uncertainty in Object Pose Determination with Three Light-Stripe Range Measurements," IEEE Transactions on Robotics and Automation, Vol. 11, No.5, pp.741-747, 1996

M. Uenohara and T. Kanade, "Vision-Based Object Registration for Real-Time Image Overlay," International Journal of Computers in Biology and Medicine, Vol 25, No. 2, pp. 249-260, March 1995.

M.D. Wheeler and K. Ikeuchi, "Sensor Modeling, Probabilistic Hypothesis Generation, and Robust Localization for Object Recognition," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 17, No. 3, March, 1995.

D.A. Simon, M. Hebert and T. Kanade, "Techniques for Fast and Accurate Intrasurgical Registration," Journal of Image-Guided Surgery, Vol.1, pp.17-29, April 1995.

M. Hebert, K. Ikeuchi, and H. Delingette, "A Spherical Representation for Recognition of Free-Form Surfaces," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 17, No. 7, July, 1995, pp. 681-690.

K. Higuchi, M. Hebert, and K. Ikeuchi, "Building 3-D Models from Unregistered Ranges Images," CVGIP-GMIP, Vol. 57, No. 4, July, 1995, pp. 315-333.

S. B. Kang and K. Ikeuchi, "Temporal segmentation of tasks from human hand motion," IEEE Trans R&A, 11(5) 670:681, Oct 1995.

H. Shum, K. Ikeuchi, and R. Reddy, "Principal Component Analysis with Missing Data and its Application to Polyhedral Object Modeling," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 17, No. 9, September, 1995, pp. 854-867.

S. Kang and K. Ikeuchi, "Toward Automatic Robot Instruction from Perception - Temporal Segmentation of Tasks from Human Hand Motion," IEEE Trans on Robotics and Automation, Vol. 11, No. 5, October, 1995, pp. 670 - 681.

T. Kanade and M. Okutomi, "A Stereo Matching Algorithm with an Adaptive Window: Theory and Experiment," IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol. 16, No. 9, pp. 920-932, September 1994.

Y. Sato and K. Ikeuchi, "Temporal-color space analysis of reflection," Journal of Optical Society of America A, Vol. 11, No. 11, November, 1994, pp. 2990 – 3002.

K. Ikeuchi and T. Suehiro, "Toward an Assembly Plan from Observation, Part I: Task Recognition with Polyhedral Objects," IEEE Trans. Robotics and Automation, Vol. 10, No. 3, June, 1994, pp. 368-385.

(b) Papers published in Conference Proceedings

M. Han and T. Kanade, "Creating 3D Models with Uncalibrated Cameras", proceeding of IEEE Computer Society Workshop on the Application of Computer Vision (WACV2000), December 2000.

H. Schneiderman and T. Kanade, "A Statistical Model for 3D Object Detection Applied to Faces and Cars", Proceedings of the 2000 IEEE Conference on Computer Vision and Pattern Recognition (CVPR '00), June 2000.

D.D. Morris and T. Kanade, "Image-Consistent Surface Triangulation", Proceedings of the 2000 IEEE Conference on Computer Vision and Pattern Recognition (CVPR 2000), IEEE Computer Society, Vol. 1, June 2000, pp. 332-338.

M. Han and T. Kanade, "Reconstruction of a Scene with Multiple Linearly Moving Objects", Proceedings of the 2000 IEEE Conference on Computer Vision and Pattern Recognition (CVPR 2000), June 2000

S. Vedula, S. Baker, S. Seitz, and T. Kanade, "Shape and Motion Carving in 6D" Computer Vision and Pattern Recognition (CVPR), June 2000.

M. Kimura, H. Saito, and T. Kanade, "3D Voxel Construction based on Epipolar Geometry", Proceedings of the 1999 International Conference on Image Processing, Vol. 3, October 1999, pp. 135 - 139.

H. Saito, S. Baba, M. Kimura, S. Vedula, and T. Kanade, "Appearance-Based Virtual View Generation of Temporally-Varying Events from Multi-Camera Images in the 3D Room", Proceedings of Second International Conference on 3-D Digital Imaging and Modeling, October 1999, pp. 516 - 525.

S. Vedula, S. Baker, P. Rander, R. Collins, and T. Kanade, "Three-Dimensional Scene Flow", Proceedings of the 7th International Conference on Computer Vision, Vol. 2, September 1999, pp. 722 - 729.

H. Saito and T. Kanade, "Shape Reconstruction in Projective Grid Space from Large Number of Images", IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR '99), June 1999.

V. Broz, O. Carmichael, S. Thayer, J. Osborn, and M. Hebert, "ARTISAN: An Integrated Scene Mapping and Object Recognition System," American Nuclear Society 8th Intl. Topical Meeting on Robotics and Remote Systems, American Nuclear Society, April, 1999.

D. Zhang and M. Hebert, "Harmonic Maps and Their Applications in Surface Matching," IEEE Conference on Computer Vision and Pattern Recognition (CVPR '99), Vol. 2, 1999.

Y. Takeuchi and M. Hebert, "Evaluation of Image-Based Landmark Recognition Techniques," tech. report CMU-RI-TR-98-20, Robotics Institute, Carnegie Mellon University, July, 1998.

Schneiderman and T. Kanade, "Probabilistic Modeling of Local Appearance and Spatial Relationships for Object Recognition," Proceeding of the IEEE Conference of Computer Vision and Pattern Recognition (CVPR'98) pp. 45-51, 1998.

Rowley, S. Baluja, and T. Kanade, "Rotation-Invariant Neural Network-based Face Detection," Proceeding of the IEEE Conference of Computer Vision and Pattern Recognition (CVPR'98) pp. 38-44, 1998.

P.J. Narayanan, P.W. Rander, T. Kanade, "Constructing Virtual Worlds using Dense Stereo,"6th International Conference on Computer Vision (ICCV), Bombay, INDIA, pp. 3-10, January 4-7, 1998.

D. D. Morris, T.Kanade, "A Unified Factorization Algorithm for Points: Line-Segments and Planes with Uncertainty Models," Proc. 6th International Conference on Computer Vision (ICCV), Bombay, INDIA, pp. 696-702, January 4-7, 1998.

T. Sato, T. Kanade, E. Hughes and M. Smith, "Video OCR for Digital News Archives," Proc. of IEEE International Workshop on Content-Based Access of Image and Video Databases (CAIVD '98), India, January 3, 1998.

A. Johnson, O. Carmichael, D.F. Huber, and M. Hebert, "Toward a General 3-D Matching Engine: Multiple Models, Complex Scenes, and Efficient Data Filtering," Proceedings of the 1998 Image Understanding Workshop (IUW), November, 1998, pp. 1097-1107.

J. Hancock, M. Hebert, and C. Thorpe, "Laser Intensity-Based Obstacle Detection," Proceedings 1998 IEEE/RSJ International Conference On Intelligent Robotic Systems (IROS '98), Vol. 3, October, 1998, pp. 1541 - 1546.

O. Carmichael and M. Hebert, "Unconstrained Registration of Large 3D Point Sets for Complex Model Building," Proceedings 1998 IEEE/RSJ International Conference On Intelligent Robotic Systems (IROS '98), Vol. 1, October, 1998, pp. 360 - 367.

A. Johnson and M. Hebert, "Efficient multiple model recognition in cluttered 3-D scenes," Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR '98), June, 1998, pp. 671 - 677.

Y. Takeuchi and M. Hebert, "Finding Images of Landmarks in Video Sequences," Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR '98), June, 1998.

P. Janardhan, M. Hebert, and K. Ikeuchi, "The space-time map applied to Drosophila embryogenesis," Proceedings of the Workshop on Biomedical Image Analysis, June, 1998, pp. 144 - 153.

D. Zhang, M. Hebert, A. Johnson, and Y. Liu, "On Generating Multi-resolution Representations of Polygonal Meshes," Proc. ICCV '98, 1998.

P. Janardhan, M. Hebert, and K. Ikeuchi, "The space-time map applied to Drosophila embryogenesis," Proceedings of the Workshop on Biomedical Image Analysis, June, 1998, pp. 144 - 53.

M. Wheeler, Y. Sato, and K. Ikeuchi, "Consensus surfaces for modeling 3D objects from multiple range images," Proceedings of ICCV '98, January, 1998, pp. 917 – 924.

P. Rander, P.J. Narayanan and T. Kanade, "Virtualized Reality: Constructing Time-Varying Virtual Worlds from Real Events," IEEE Visualization '97, pp. 277-283, 1997.

T. Kanade, S. Satoh, Y. Nakamura, "Accessing Video Contents: Cooperative Approach between Image and Natural Language Processing," International Symposium on Research, Development and Practice in Digital Libraries (ISDL), Tsukuba, Ibaraki, Japan, pp.143-150, November 18-21, 1997.

Y. Nakamura and T. Kanade, "Semantic Analysis for Video Contents Extraction - Spotting by Association in News Video," Proceedings of The Fifth ACM International Multimedia Conference, November 1997.

Frank Dellaert and Chuck Thorpe, "Robust Car Tracking using Kalman filtering and Bayesian templates," SPIE Conference on Intelligent Transportation Systems, Pittsburgh, PA, October,1997.

N. Chiba, T. Kanade, "A tracker for broken and Closely-Spaced Lines," International Symposium on Real-Time Imaging and Dynamic Analysis, Hakodate, Hokkaido, Japan, June 2-5, 1997.

S. Satoh, Y. Nakamura and T. Kanade, "Name-It: Naming and Detecting Faces in Video by the Integration of Image and Natural Language Processing," Proc. of International Joint Conference on Artificial Intelligence (IJCAI-97), pp. 1488-1493, 1997.

D. Zhang and M. Hebert, "Multi-Scale Classification of 3-D Objects," IEEE Conference on Computer Vision and Pattern Recognition, June, 1997, pp. 864 - 869.

A. Johnson and M. Hebert, "Surface Registration by Matching Oriented Points," International Conference on Recent Advances in 3-D Digital Imaging and Modeling, May, 1997, pp. 121-128.

G.V. Paul and K. Ikeuchi, "Representing the Motion of Object in Contact using Dual Quaternions and its Applications," tech. report CMU-RI-TR-97-31, Robotics Institute, Carnegie Mellon University, August, 1997.

Y. Takeuchi, P. Gros, M. Hebert, and K. Ikeuchi, "Visual Learning for Landmark Recognition," Image Understanding Workshop, May, 1997.

G. Paul and K. Ikeuchi, "A Quasi-Linear Method for Computing and Projecting onto C-Surfaces: Planar Case," IEEE International Conference on Robotics and Automation, Vol. 3, April, 1997, pp. 2032-2037.

Robert T. Collins, "Multi-Image Focus of Attention for Rapid Site Model Construction," In Proceedings of IEEE Computer Vision and Pattern Recognition (CVPR), pp. 575-581, San Juan, Puerto Rico, June, 1997.

A. Johnson and M. Hebert, "Recognizing objects by matching oriented points," Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR '97),, June, 1997, pp. 684 - 689.

Y. Sato, M. Wheeler, and K. Ikeuchi, "Object shape and reflectance modeling from observation," Proceedings of ACM SIGGRAPH 97, in Computer Graphics Proceedings, Annual Conference Series 1997, ACM SIGGRAPH, August, 1997, pp. 379 - 387.

G. Paul, Y. Jiar, M.D. Wheeler, and K. Ikeuchi, "Modelling Human Assembly Actions from Observation", IEEE/SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems, December, 1996.

Y. Sato and K. Ikeuchi, "Recovering shape and reflectance properties from a sequence of range and color mages," IEEE/SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems '96, December, 1996, pp. 493-500.

G. Paul and K. Ikeuchi, "Modeling Planar Assembly Paths from Observation," IEEE/RSJ International Conference of Intelligent Robots and Systems, Vol. 2, November, 1996, pp. 520 - 525.

Y. Sato and K. Ikeuchi, “Photorealistic object generation from observation for virtual reality applications,” International Conference on Artificial Reality and Tele-Existance '96, November, 1996, pp. 47-58.

P. Rander, P.J. Narayanan and T. Kanade, “Recovery of Dynamic Scene Structure from Multiple Image Sequences,” Proceedings IEEE/ SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems, Washington, DC, pp.305-312, December 8-11, 1996.

YM. Uenohara, T. Kanade, “Geometric Invariants for Verification in 3-D Object Tracking,” IEEE/RSJ International Conference on Intelligent Robots and System (IROS‘96), pp785-790, Nov 4-8, 1996.

H. Rowley, S. Baluja and T. Kanade, “Neural Network-Based Face Detection,” Proc. at Int’l Conference on Computer Vision and Pattern Recognition 96 (CVPR ‘96), San Francisco, CA, pp.203-208, June 18 - 20, 1996.

H. Shum, M. Hebert, and K. Ikeuchi, “On 3D shape similarity,” Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR '96), June, 1996, pp. 526 - 531.

L. Quan and T. Kanade, “A Factorization Method for Affine Structure from Line Correspondences,” Proc. at Int’l Conference on Computer Vision and Pattern Recognition 96 (CVPR ‘96), San Francisco, CA, pp.803-808, June 18 - 20, 1996.

H. Shum, M. Hebert, and K. Ikeuchi, “On 3D shape similarity,” Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR '96), June, pp. 526 – 531, 1996.

Krumm and Shafer, "Texture Segmentation and Shape in the Same Image," Proceedings of the International Conference on Computer Vision, Cambridge, MA, pp. 121-127, , June 1995

Xiong and Shafer, "Hypergeometric Filters for Optical Flow and Affine Matching," Proceedings of the International Conference on Computer Vision, Cambridge, MA, pp. 771-776, , June 1995.

J. Costeria and T. Kanade, "A multi-body factorization method for motion analysis," Proc of ICCV, 1071:1076, June 1995.

S. Kang and K. Ikeuchi, “A Robot System that Observes and Replicates Grasping Tasks,” The Fifth International Conference on Computer Vision, June, 1995, pp. 1093-1099.

Y. Sato and K. Ikeuchi, “Reflectance Analysis Under Solar Illumination,” IEEE Workshop on Physics-Based Modeling and Computer Vision, June, 1995, pp. 180-187.

J. Miura and K. Ikeuchi, “Task-Oriented Generation of Visual Sensing Strategies,” The Fifth International Conference on Computer Vision, June, 1995, pp. 1106-1113.

J. Rehg, T. Kanade, “Model-Based Tracking of Self-Occluding Articulated Objects,”5th International Conference on Computer Vision(ICCV), Cambridge, MA, pp. 612-617, June 20-23, 1995.

F. Solomon and K. Ikeuchi, “An Illumination Planner for Lambertian Polyhedral Objects,” IEEE International Conference Robotics and Automation, Vol. 2, May, 1995, pp. 719- 725.

H.A. Rowley, S. Baluja and T. Kanade, “Human Face Detection in Visual Scenes,” Neural Information Processing Systems (NIPS'95), Denver CO, November 27-December 2, 1995.

T. Kanade, D. A. Simon, R. V. O’Toole, M. K. Blackwell, F. Morgan and A. M. DiGioia, “Accuracy Validation in Image-Guided Orthopaedic Surgery,” MRCAS 95, Baltimore, MD, November 1995.

T. Kanade, P. J. Narayanan, and P. Rander, "Virtualized Reality: Being Mobile in a Visual Scene," Proceedings of ICAT/VRST '95 (International Conference on Artificial Reality and Tele-Existence/ Conference on Virtual Reality Software and Technology), Chiba, Japan, pp. 133-142, Nov 21-22, 1995.

T. Kanade, P. J. Narayanan, P. W. Rander, "Virtualized (Not Virtual) Reality," 15th International Conference on Display Technology (Asia Display 95), Japan, Oct. 1995.

T. Kanade, P. J. Narayanan, P. W. Rander, "Virtualized Reality: Concepts and Early Results," IEEE Workshop on the Representation of Visual Scenes, Cambridge, MA, pp. 69-76, June 24, 1995.

S.B. Kang, J. Webb, L. Zitnick, T. Kanade, "A Multibaseline Stereo System with Active Illumination and Real-Time Image Acquisition,"5th International Conference on Computer Vision(ICCV), Cambridge, MA, pp. 88-93, June 20-23, 1995.

J. Costeira and T. Kanade, "Factorization Method for Motion Analysis," 5th Int'l Conference on Computer Vision (ICCV), Cambridge, MA, pp. 1071-1076, June 20-23, 1995.

M. Uenohara and T. Kanade, "Vision-Based Object Registration for Real-Time Image Overlay," Proc. of 1995 Conference on Computer Vision, Virtual Reality and Robotics in Medicine, Nice, France, April 1995.

G. Paul and K. Ikeuchi, "Modelling Planar Assembly Tasks: Representation and Recognition," Proceedings of International Conference on Intelligent Robots and Systems, Vol. 1, August, 1995, pp. 17-22.

S. Kang and K. Ikeuchi, "Robot Task Programming by Human Demonstration: Mapping Human Grasps to Manipulator Grasps," IEEE/RJS International Conference on Intelligent Robots and Systems, Vol. 1, September, 1994, pp. 97-104.

H. Shum, K. Ikeuchi, and R. Reddy, "Virtual reality modeling from a sequence of range images," IEEE / RJS International Conference on Intelligent Robots and Systems, Vol. 1, September, 1994, pp. 703-710.

J. Ponce, R. Bajcsy, D. Metaxas, T. Binford, D. Forsyth, M. Hebert, K. Ikeuchi, A. Kak, L. Shapiro, S. Sclaroff, A. Pentland, and G. Stockman, "Object representation for object recognition," Proc of IEEE conf. on Computer Vision and Pattern Recognition, June, 1994, pp. 147-152.

J. Poelman and T. Kanade, "A Paraperspective Factorization Method for Shape and Motion Recovery," Proc. of Third European Conference on Computer Vision (ECCV '94), Stockholm, Sweden, Vol. I, pp. 97-108, May 1994.

J. M. Rehg and T. Kanade, "Visual Tracking of High DOF Articulated Structures: an Approach to Human Hand Tracking," Proc. of Third European Conference on Computer Vision, Stockholm, Sweden, Vol. 1, pp. 35-46, May 1994.

K. Kemmotsu and T. Kanade, "Sensor Placement Design for Object Pose Determination with Three Light-Stripe Range Finders," Proc. of the 1994 IEEE International Conference on Robotics and Automation (ICRA'94), San Diego, CA, May 8-13, 1994.

K. Higuchi, M. Hebert, and K. Ikeuchi, "Building 3D models from Unregistered Range Images," Proceedings of IEEE Conference on Robotics and Automation (ICRA '94), Vol. 3, May, 1994, pp. 2248 - 2253

D. Simon, M. Hebert, and T. Kanade, "Real-time 3-D pose estimation using a high-speed range sensor," Proceedings of IEEE International Conference on Robotics and Automation (ICRA '94), Vol. 3, May, 1994, pp. 2235-2241.

K. Higuchi, H. Delingette, M. Hebert, and K. Ikeuchi, "Merging Multiple Views Using a Spherical Representation," Proc of 2nd IEEE Workshop on CAD-based Vision, February, 1994, pp. 124 - 131.

S. Kang and K. Ikeuchi, "Determination of Motion Breakpoints in a Task Sequence from Human Hand Motion," Proc. IEEE Int'l Conf. on Robotics and Automation (ICRA '94), Vol. 1, May, 1994, pp. 551 - 556.

S. Kang and K. Ikeuchi, "Grasp Recognition and Manipulative Motion Characterization from Human Hand Motion Sequences," Proc. IEEE Int'l Conf. on Robotics and Automation (ICRA '94), Vol. 2, May, 1994, pp.1759 – 1764.

K.D. Gremban and K. Ikeuchi, "Planning Multiple Observations for Object Recognition," International Journal of Computer Vision, Vol. 12, No. 2-3, May, 1994, pp. 137-172.

M.D. Wheeler and K. Ikeuchi, "Sensor modeling, Probabilistic Hypothesis Generation, and Robust Localization for Object Recognition," Proc of 2nd IEEE Workshop on CAD-based Vision, February, 1994, pp. 46 - 53.

H. Delingette, M. Hebert, and K. Ikeuchi, "A Spherical Representation for the Recognition of Curved Objects," International Conference on Computer Vision, May, 1993, pp. 103 - 112.

Invention

United States Patent No.6,084,979: Method for Creating Virtual Reality (with Narayanan, India, and Rander); Filed June 20, 1996; Issued July 4, 2000.

United States Patent No. 6,002,859: Apparatus and Method for Facilitating the Implantation of Artificial Components in Joints (with DiGioia, Simon, Jaramaz, Blackwell, Morgan and O'Toole), Filed November 12, 1998; Issued December 14, 1999.

Invention Disclosure to Carnegie Mellon University 98-035, "3D Surface Matching"

European Patent No. 0786114: Method and Apparatus for Creating a Searchable Digital Video Library and a System and Method of Using Such a Library; Issued August 5, 1998.

List of All Participating Scientific Personnel and Advanced Degrees Earned

Faculty:

Takeo Kanade, Professor
Steven Shafer, Associate Professor
Katsushi Ikeuchi, Principal Research Scientist
Robert Collins, Research Scientist
Charles Thorpe, Senior Research Scientist
Stuart Fairly, Post Doctoral Fellow

Students:

Kan Deng	Ph. D
Joyoni Dey	Ph. D
Paul George	Ph. D
Qifa Ke	
David Larose	Ph.D
Bruce Maxell	Ph. D
Mark Maimone	Ph. D
Conrad Poelman	Ph. D
Peter Rander	Ph. D
Henry Rowley	Ph. D
Yoichi Sato	Ph. D
Henry Schneiderman	Ph. D
Frank Solomon	Ph. D
Ron Stone	Ph. D
Sundar Vedula	Ph. D
Mark Wheeler	Ph. D
Yalin Xiong	Ph. D