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14. ABSTRACT
We propose to apply recently developed methods of sparse representation and dimensionality reduction to multimodality image and video databases. Our research will consist of three interconnected components: 1) multimodality feature extraction from the database; 2) informationtheoretic similarity measures for pairwise matching; 3) hierarchical similarity-based clustering and database updating. Information-theoretic measures, sparse approximation and dimensionality reduction will play key roles in our work. They will allow us to reduce complexity, accelerate query matching times, improve specificity of the query matches, and incorporate robustness

15. SUBJECT TERMS
Video Indexing and retrieval, view/pose invariant representations, information geometric embeddings, computer vision, information retrieval, anomaly detection

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Alfred Hero
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Report Title

Final Report: Sparse representation of multimodality sensing databases for data mining and retrieval

ABSTRACT

We propose to apply recently developed methods of sparse representation and dimensionality reduction to multimodality image and video databases. Our research will consist of three interconnected components: 1) multimodality feature extraction from the database; 2) informationtheoretic similarity measures for pairwise matching; 3) hierarchical similarity-based clustering and database updating. Information-theoretic measures, sparse approximation and dimensionality reduction will play key roles in our work. They will allow us to reduce complexity, accelerate query matching times, improve specifcity of the query matches, and incorporate robustness to noise and other distortions. Experimental validation will be performed by a combination of simulation and experiment on multimodality databases. As part of this proposal we propose to build a small scale experimental LADAR/EO video acquisition testbed.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/11/2014	29.00	K.-J. Hsiao, J. Kulezsa, A.O. Hero. Social Collaborative Retrieval, IEEE JOURNAL OF SELECTED TOPICS IN in Signal Processing, (04 2014): 660. doi:
08/12/2013	20.00	Mark Kliger, Kevin S. Xu, Alfred O. Hero. A regularized graph layout framework for dynamic network visualization, J. Data Mining and Knowledge Discovery, (08 2012): 1. doi: 10.1007/s10618-012-0286-6
08/12/2013	26.00	Kumar Sricharan, Dennis Wei, Alfred O. Hero III. Ensemble estimators for multivariate entropy estimation, IEEE Trans on Information Theory, (07 2013): 4374. doi:
08/30/2012	6.00	A.O. Hero, K. Todros. On Measure Transformed Canonical Correlation Analysis, IEEE Trans. on Signal Processing, (09 2012): 4570. doi:
08/30/2012	7.00	S. Savarese, X. Chen, A.O. Hero. Multimodal Video Indexing Using Directed Information, IEEE Transactions on Multimedia, (02 2012): 3. doi:
08/30/2012	8.00	M. Telaprolu, M. Sun, H. Lee, S. Savarese. An Efficient Branch-and-Bound Algorithm for Optimal Human Pose Estimation, Pattern Analysis Machine Intelligence (PAMI), ( ): 0. doi:
TOTAL:		**6**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
04/03/2015 40.00	Ko-Jen Hsiao, Jeff Calder, Alfred O. Hero III. Pareto-depth for Multiple-query Image Retrieval, arXiv:1402.5176, (02 2014): 0. doi:
08/12/2013 21.00	K. Todros, A.O. Hero. On Measure Transformed Canonical Correlation Analysis, IEEE Trans. on Signal Processing, (09 2012): 4570. doi:
08/12/2013 24.00	Jef Calder , Selim Esedo$_{\top}$glu , Alfred O. Hero. A Hamilton-Jacobi equation for the continuum limit of non-dominated sorting, SIAM Journal on Mathematical Analysis (SIMA), (02 2013): 0. doi:
TOTAL:	**3**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Alfred Hero, “Small sample community detection in massive data sets,” Plenary talk, IEEE CAMSAP Workshop, St Martins. Dec 2013.

Alfred Hero, “Spatio-temporal graphical models for high dimensional network data,” Keynote talk, Network Theory Symposium, IEEE GlobalSIP Conference, Austin TX., Dec 2013.

Alfred Hero, “Sparsity regularized image reconstruction,” Quantitative Non-Destructive Evaluation (QNDE), Keynote talk, Boise ID, July 2014.

Alfred Hero, “Correlation mining in large networks with limited samples,” Keynote talk, IEEE International Telecomunications Symposium, Sao Paolo Brazil. Aug. 2014.

Silvio Savarese, “Perceiving the 3D world”, invited talk at the Large Scale Visual Commerce workshop, in conjunction of ICCV 2013, Australia, December 2013

Number of Presentations: 5.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
04/03/2015	38.00	Byung-soo Kim, Pushmeet Kohli, Silvio Savarese. 3D Scene Understanding by Voxel-CRF, ICCV 2013. 01-DEC-13, . : ,
04/03/2015	37.00	Y. Xiang, S. Savarese. Object Detection by 3D Aspectlets and Occlusion Reasoning, ICCV 2013. 01-DEC-13, . : ,
08/11/2014	30.00	J. Calder, S. Esedoglu, A.O. Hero. A continuum limit for non-dominated sorting, Conference on Information Theory and its Applications (ITA), San Diego. 01-FEB-14, . : ,
11/17/2011	2.00	Xu Chen, Alfred O. Hero. Video indexing and retrieval using Fisher information non-linear embedding (FINE), SPIE Electronic Imaging Conference. 23-JAN-11, . : ,
11/17/2011	4.00	Liang Mei, Jingen Liu, Alfred Hero, Silvio Savarese. Robust object pose estimation via statistical manifold modeling, 13th Intl Conference on Computer Vision (ICCV). 06-NOV-11, . : ,
11/17/2011	5.00	Kihyuk Sohn, Dae Yon Jung, Honglak Lee, Alfred O. Hero III. Efficient learning of sparse, distributed, convolutional feature representations for object recognition, 13th Intl Conf on Computer Vision (ICCV). 06-NOV-11, . : ,
TOTAL:		**6**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
08/11/2014 31.00	Pin-Yu Chen, Alfred O. Hero III. Local Fiedler Vector Centrality for Detection of Deep and Overlapping Communities in Networks, Proc. of IEEE Conf. on Acoustics, Speech and Signal Processing (ICASSP) 2014. Florence Italy,. 04-MAY-14, . : ,
08/11/2014 33.00	A.O. Hero, K. Todros. Robust Measure Transformed MUSIC for DOA Estimation, Proc. of IEEE Conf. on Acoustics, Speech and Signal Processing (ICASSP) 2014. 04-MAY-14, . : ,
08/11/2014 34.00	Min Sun, Wan Huang, Silvio Savarese. Find the Best Path: an Efficient and Accurate Classifier for Image Hierarchies, Proceedings of the International Conference in Computer Vision (ICCV) 2013. 03-DEC-13, . : ,
08/11/2014 36.00	Pin-Yu Chen, Alfred O. Hero III. Node Removal Vulnerability of the LargestComponent of a Network, Proceedings of IEEE GlobalSIP . 05-DEC-13, . : ,
08/12/2013 22.00	K.-J. Hsiao, K. S. Xu, J. Calder , A. O. Hero. Multi-criteria Anomaly Detection using Pareto Depth Analysis, Proc. of Neural Information Processing Systems (NIPS). 05-DEC-12, . : ,
08/12/2013 25.00	S. Xu, B. Kim, S. Savarese. Accurate Localization of 3D Objects from RGB-D Data using Segmentation Hypotheses,, IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 25-JUN-13, . : ,
08/12/2013 23.00	Kumar Sricharan, Alfred O. Hero III. Ensemble weighted kernel estimators for multivariate entropy estimation, Proc. of Neural Information Processing Systems (NIPS. 05-DEC-12, . : ,
08/30/2012 12.00	X, Chen, S. Savarese, A.O. Hero. Multimodal Video Indexing Using Directed Information, IEEE Transactions on Multimedia, vol 14, no 1, pp. 3-16, Feb 2012. . 01-FEB-12, . : ,
08/30/2012 13.00	J. Li, L. Mei, AO Hero, S. Savarese. Robust object pose estimation via statistical manifold modeling, Proceedings of 13th Intl Conf on Computer Vision (ICCV), Barcelona, Nov. 2011. . 01-NOV-11, . : ,
08/30/2012 14.00	K. Sohn, D-Y Jung, H Lee, A.O. Hero. Effcient Learning of Sparse, Distributed, Convolutional Feature Representations for Object Recognition , Proceedings of 13th Intl Conf on Computer Vision (ICCV), Barcelona. 01-NOV-11, . : ,
08/30/2012 15.00	Z. Syed, A.O. Hero, X. Chen. EEG spatial decoding with shrinkage regularized directed information assessment, IEEE ICASSP, Kyoto.. 25-MAR-12, . : ,
08/30/2012 16.00	Xu Chen, Yilun Chen, Alfred Hero. Shrinkage Fisher Information Embedding of High Dimensional Feature Distributions, Proceedings of Asilomar Conference, Pacific Grove. 01-JAN-11, . : ,
08/30/2012 17.00	M. Sun, M. Telaprolu, H. Lee, S. Savarese. An Efficient Branch-and-Bound Algorithm for Optimal Human Pose Estimation, IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2012.. 19-JUN-12, . : ,

08/30/2012 18.00 M. Telaprolu, H. Lee, S. Savarese, M. Sun. Efficient and Exact MAP Inference using Branch and Bound, 15th International Conference on Artificial Intelligence and Statistics (AISTATS). 01-APR-12, . : ,

08/30/2012 19.00 Y. Xiang, S. Savarese. Estimating the Aspect Layout of Object Categories, EEE Conference on Computer Vision and Pattern Recognition (CVPR). 19-JUN-12, . : ,

TOTAL: 15

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/11/2014	27.00	Kevin S. Xu, Mark Kliger, Alfred O. Hero III. Adaptive Evolutionary Clustering, Journal of Data Miningand Knowledge Discovery (07 2013)
08/11/2014	28.00	Selim Esedoglu, Alfred O. Hero, Jeff Calder. A PDE-based approach to non-dominated sorting, SIAM J Numerical Analsis (10 2013)
08/11/2014	35.00	S. Savarese, R. Mottaghi. A Unified Framework for Object Detection, 3D Pose Estimation, and Sub-category Recognition, NIPS (submitted) 2014 (05 2014)
11/17/2011	1.00	Raviv Raich, William G. Finn, Kevin M. Carter, Alfred O. Hero III. Information-Geometric Dimensionality Reduction, IEEE Signal Processing Magazine (11 2011)
11/17/2011	3.00	Xu Chen, Alfred Hero, Silvio Savarese. Multimodal Video Indexing Using Directed Information, IEEE Transactions on Multimedia (11 2011)

TOTAL: 5

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Lifetime career award: IEEE Signal Processing Society Technical Achievement Award, given at the 2014 Intl. Conf on Acoust., Speech, and Signal Processing, Florence Italy. May 2014.

Best paper award: IEEE CAMSAP 2013 Best Student Paper Competition, awarded 2nd place for a paper coauthored with my former student Zhaoshi Meng and former post-docs DennisWei and Ami Wiesel entitled "Marginal Likelihoods for Distributed Estimation of Graphical Model Parameters," IEEE Computational Advances in Multi-Sensor Adaptive Processing workshop, St Martins. Dec 2013.

Best paper award: IEEE ICIP 2013 Best Paper Award, for a paper co-authored with former student Paul Shearer and colleague Anna Gilbert entitled "Correcting Camera Shake by Incremental Sparse Edge Approximation," at the 2013 IEEE Intl. Conf. on Image Processing, Melbourne Australia. Sept. 2013.

Plenary talk: "Small sample community detection in massive data sets," IEEE CAMSAP Workshop, St Martins. Dec 2013.

Keynote: "Resource constrained adaptive sensing," New Sensing and Statistical Inference Methods Symposium, IEEE GlobalSIP Conference, Austin TX. Dec 2013.

Keynote: "Spatio-temporal graphical models for high dimensional network data," Network Theory Symposium, IEEE GlobalSIP Conference, Austin TX., Dec 2013.

Keynote: "Sparsity regularized image reconstruction," Quantitative Non-Destructive Evaluation (QNDE), Boise ID, July 2014.

Keynote: "Correlation mining in large networks with limited samples," IEEE International Telecomunications Symposium, Sao Paolo Brazil. Aug. 2014.

Plenary: "Correlation mining for imaging and multidimensional signal processing," IEEE Intl Conference on Image Processing, Paris France. Oct. 2014.

Alfred Hero was invited to give 6 plenary lectures including the following:

1. "Small sample community detection in massive data sets," IEEE CAMSAP Workshop, Dec 2013.
2. "Resource constrained adaptive sensing," New Sensing and Statistical Inference Methods Symposium, IEEE GlobalSIP Conference, Dec 2013.
3. "Spatio-temporal graphical models for high dimensional network data," Network Theory Symposium, IEEE GlobalSIP Conference, Dec 2013.
4. "Information-driven multimodality fusion," AFRL/UES Workshop on Data Fusion for the Detection of Rare and Anomalous Events, Dec 2012."
5. "Graphical modeling for high dimensional data analysis," (Keynote 1)" Solar Information Processing Workshop (SIP) VI, MSU Bozeman, Aug. 14 2012.
6. "Learning with entropic graphs," (Keynote Solar Information Processing Workshop (SIP) VI, MSU Bozeman, Aug. 15 2012.

Alfred Hero won a Notable Paper award for his work on graphical models from AISTATS 2013 for the paper: Z. Meng, D. Wei, A. Wiesel, A. Hero, "Distributed Learning of Gaussian Graphical Models via Marginal Likelihoods," AISTATS Scottsdale AZ. April 2013.

Alfred Hero was awarded the University of Michigan Rackham Distinguished Faculty Achievement Award in 2011.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Liang Mei	0.50	
Min Sun	0.50	
Yu Xiang	0.50	
Dae Yon Jung	0.50	
Ko-Jen Hsiao	0.50	
Zhaoshi Meng	0.50	
Yu-Wei Chao	0.50	
Jinyoung Hwang	0.50	
Sung Jin Hwang	0.50	
Anush Mohan	0.50	
FTE Equivalent:	**5.00**	
Total Number:	**10**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Sung Jin Hwang	1.00
Xu Chen	1.00
John Alexander Kulesza	0.50
Greg Newstadt	1.00
Koby Todros	1.00
FTE Equivalent:	**4.50**
Total Number:	**5**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Alfred Hero	0.00	No
Silvio Savarese	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Ko-Jen Hsiao	
Min Sun	
Sung Jin Hwang	
Total Number:	**3**

Names of other research staff

NAME	PERCENT_SUPPORTED
Yue Hou	0.10
Akshay Kumar Jain Pokarma	0.10
Taoran Yan	0.05
Anuj Chandawalla	0.05
Chang Wang	0.05
FTE Equivalent:	**0.35**
Total Number:	**5**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Alfred Hero visited ARL in June 2014 where he met with ARL researchers to discuss, among other things, research under this grant. ARL researchers with whom Al Hero interacted included: Lance Kaplan, Brian Sadler, and Nasser Nasrabadi.

The Pareto multiple query image retrieval software implementing the method reported in publication [26] was transitioned to ARL and is under evaluation.

Supported student Brandon Oselio did an internship at ARL under Lance Kaplan in summer 2014.

Alfred Hero visited Army Research Laboratory for one day in Feb 2013. He had discussions with Lance Kaplan, Brian Sadler, Nasser Nasrabadi, Terry Moore and Tien Pham on topics relevant to this project.

Two of Alfred Hero's PhD students (Brandon Oselio and Ted Tsiligaridis) visited ARL as interns in summer 2013.

Alfred Hero has had several meetings with ARL researchers Brian Sadler, Laurel Sadler and Robert Winkler on designing a human factors experiment at ARL using the Pareto frontier search engine (https://dl.dropboxusercontent.com/u/13611327/paretoretrievalgui.zip) developed under this project.

Alfred Hero helped Liyi Dai organize a Government Panel of DoD researchers and research managers in Ann Arbor at the IEEE Statistical Signal Processing Workshop (A Hero was General Chair).

Alfred Hero visited Army Research Laboratory for one day in January 2012. He had discussions with Lance Kaplan, Brian Sadler, Nasser Nasrabadi, Terry Moore on topics relevant to this project.

Two of Alfred Hero's PhD students visited ARL as interns in summer 2012.

Alfred Hero met with ARL researchers Brian Sadler and Terry Moore at College Park during the FFT symposium held in the Dept of Mathematics at Univ of Maryland.

Alfred Hero organized an ARO sponsored workshop in April in Annarbor on Sensor Information Estimation and Exploitation with the help of Army research and development center researcher Donald Waagen.

Alfred Hero helped Liyi Dai organize a Government Panel of DoD researchers and research managers in Ann Arbor at the IEEE Statistical Signal Processing Workshop (A Hero was General Chair).

Sparse representation of multimodality sensing databases for data mining and retrieval

Final report for period 07/1/09 to 06/30/14.

Alfred O. Hero, PI, EECS Department, University of Michigan, Ann Arbor, MI 48109-2122, USA
Silvio Savarese, co-PI, CS Department, Stanford University, Stanford, CA USA

Army Research Office Grant: W911NF-09-1-0210, started 07/01/2009

Overall objective of project:

The objective is to develop sparse representation and dimensionality reduction methods for robust data mining and indexing of multimodality image and video databases. The near term objective has been to establish feasibility of our information theoretic dimensionality reduction approach to this complex problem. The ultimate objective is to apply our techniques to large image and video databases, centralized or possibly distributed, in order to reduce search complexity, accelerate query matching times, improve specificity of the query matches, and incorporate robustness to noise, sampling, view point, occlusion, and other distortions in the database. Viewpoint and pose has been a main focus of the project over the past two years. Experimental validation has been and will continue to be performed by a combination of simulation and experiment on single and multi modal databases.

Our approach:

We adopted information-theoretic measures, distortion invariant representations, sparse approximation, and dimensionality reduction for our work. Sparsity and dimensionality reduction have been successfully applied to other problem domains to reduce complexity. We are demonstrating that indexing of large multimodality sensing databases can also benefit from this approach. Furthermore, since our proposed methods are strongly grounded in information theory, statistical signal processing, and machine learning, our algorithms can provide quantitative theoretical performance guarantees under the best conditions (matched model assumptions) and the worst conditions (mismatched model assumptions). This has led to a better understanding of the factors that limit system performance, as measured by a number of criteria such as: data mining false discoveries, search complexity, and probability of retrieval classification error. This theoretical component is a strength of this team and a key feature of the proposed research.

Scientific barriers:

For many Army applications it is especially important to have robust data mining and retrieval algorithms with guaranteed high sensitivity and specificity for complex databases. However, current algorithms are unable to deal effectively with complex databases arising in these applications. An example is where the algorithm must fuse information across different modalities. For instance when the user supplies a query picture from one modality, e.g., IR, while the most relevant entries of the database may come from a different modality, e.g., Radar. Another example is mining, searching, and indexing databases of high dimensional objects that are not properly registered, e.g., videos that contain common scenes or events that were acquired at different times, with different resolutions, different viewing angles, or under different lighting conditions. A third example is the common situation where there is significant uncertainty in the entries due to noise, insufficient samples, occlusion, or limited spatial resolution. While we may not specifically address all of these applications in this project, our general dimensionality reduction framework will supply tools that can be applied to them.

Significance:

The framework for mining and indexing complex databases enables new tools that are being applied to improve database object retrieval and discovery performance. These tools are being used to address problems of high significance to the Army such as multimodality image retrieval, anomaly detection in videos, and event correlation in videos.

Cumulative summary of accomplishments over the period of the grant (07/01/09-06/30/14)

We have demonstrated the capability of sparse representation and dimensionality reduction to make significant improvements in multi-modality computer vision and information retrieval problems, especially in spatio-temporal databases. Our non-incremental research has resulted in several major advances in both theory and practice. Our fundamental contributions to the mathematical theory of multi-objective database indexing and retrieval have led to more effective ways for humans to search image databases when there are multiple queries. This method has been applied to anomaly detection in surveillance videos, published in the top conference on machine learning (NIPS), multi-query image database search, submitted to IEEE Trans. On Image Processing, and social collaborative retrieval, which appeared in IEEE Journal on Selected Topics of Signal Processing. A remarkable theoretical limit was discovered that specifies a novel way to perform indexing: solve a novel Hamilton Jacobi partial differential equation instead of performing a combinatorial optimization for searching for best query matches. This theory was published in a top math journal (SIAM Math Analysis) and its indexing implementation was submitted to another top math journal (SIAM Numerical Analysis). Our development of new sparse non-parametric multimodality similarity measures (entropy, directed information, and measure-transformed CCA) has been published in the top machine learning conference (NIPS) and in the top journals on multi-media (IEEE Trans. On Multimedia) and signal processing (IEEE Trans. On Signal Processing). Our research on visualizing and modeling dynamic graphs has been published in two papers appearing in the top journal on knowledge discovery and data mining (Journal of DMKD). Soft information, such as relational annotations between objects in database, is often instantiated by graphs. Another major line of work supported by this grant has focused on object detection, pose estimation and classification using machine learning tools including a novel formulation of the branch and bound algorithm. This has led to publications to the International Conference in Computer vision (ICCV) in 2011, Computer Vision and Pattern Recognition (CVPR) conference in 2012, IASTATS 2012 and CVPR 2013. More recently, our research on hierarchical methods for large scale object classification was published at ICCV in December 2013. Finally, our framework for joint object detection, pose estimation and fine-grain categorization has been submitted to NIPS in 2014 and is currently under review.

Specific accomplishments over the period (08/1/13-06/30/14):

This past year has seen substantial progress that caps this 5 year project. Specifically, Hero reports progress on modeling and annotating databases of dynamic graphs, relevant to understanding complex time varying relational objects, e.g., interactions between groups of people or correlations between different types of observed events. Hero also reports progress on multi-objective indexing and retrieval. These are in addition to new publications in the areas of multimodality databases [27,28] and applications [29, 30] of non-linear similarity measures developed under this grant. Savarese reports results on localization of 3D Objects from a single D-RGB image, large scale object classification and joint pose estimation and object fine-grained categorization. Several publications have been submitted or have appeared [1]-[20] on work funded under this grant. The work reported in publications [1]-[21] was described in previous progress reports. Here we describe progress reported in publications [22]-[32] submitted in the past year.

Progress 1: Mining databases of dynamic graphs [21,22,23]

Data that is relational is often represented as a graph with nodes and edges. For example, this could be a relational database of various groups of people, places, and activities. Each group's pairwise interactions are represented by a graph whose nodes denote people and whose edges represent proximity or activity between the people, e.g., closeness in space or high frequency of activity-specific interaction. These relations generally evolve over time and the changes in graph connectivity and shape contain important cues on evolution of the community structure of

the people in the database. We have focused on three components of the problem of indexing and retrieval of such graph-valued objects from databases: 1) mathematical methods for visualization of dynamic graphs, important for human-interpretation of objects in the database; 2) scalable predictive modeling of dynamic graphs, important for detecting anomalous graph behaviors over time; and 3) node and edge centrality measures, important for annotation of databases of graphs according to graph topology. Last year we published our solution of the dynamic graph visualization problem in the leading journal on data mining [12]. This year we have published our solution to scalable predictive modeling using dynamic stochastic bock models [21], published in the same journal as [12]. We have also published two papers [22,23] that introduce a new measure of graph centrality, called local Fiedler centrality, that can be used to better index graph-valued objects with respect to community structure (modularity) of their topologies.

Progress 2: Multi-objective retrieval and indexing [24,25,26]
Over the past four years we have been constructing fundamental theory and practice that underpins an alternative indexing and retrieval method, which we call multi-objective retrieval and indexing. The theory has been published in a leading journal on mathematics analysis, SIAM Journal of Mathematical Analysis [17], and a numerical scheme that transitions the theory in [17] to practice was submitted last year to another leading mathematics journal, SIAM Journal of Numerical Analysis [24]. These fundamental mathematical results are remarkable since they specify a continuum limit (a partial differential equation) for the combinatorial Pareto ranking problem that is the crux of multi-objective retrieval and indexing. This year we published a synopsis of the mathematical result for engineers, which appeared in the proceedings of one pf the premier (by-invitation-only) conferences [25] in the applications of information theory. In the SIAM paper [24] we demonstrated that the pde continuum approximation leads to significant acceleration of multi-objective video anomaly detection, specifically the method introduced in [14]. We have submitted another indexing and retrieval application of this theory to the premier journal on image processing [26]. This application, called multiple query image retrieval, allows a user to peruse a database using Pareto partial ordering instead of the standard linear ordering used by today's image search engines. The software for multiple query image retrieval has been transitioned to ARL and is currently under evaluation.

Progress 4: Accurate Localization of 3D Objects from RGB-D Data using Segmentation Hypotheses [17]
In this work we focus on the problem of finding objects in 3D from RGB-D images. We propose a novel framework that explores the compatibility between segmentation hypotheses of the object in the image and the corresponding 3D map. Our framework allows discovering the optimal location of the object in 3D using a generalization of the structural latent SVM formulation in 3D as well as the definition of a new loss function defined over 3D space in training. We evaluate our method using two existing RGB-D datasets. Extensive quantitative and qualitative experimental results show that our proposed approach outperforms state-of-the-art as well as a number of baseline methods for both 3D and 2D object recognition tasks. This work was presented at the IEEE conference in Computer Vision and Pattern Recognition (CVPR, June 2013) [17]

Progress 5: ***An Efficient and Accurate Classifier for Image Hierarchies [31]***. Many methods have been proposed to solve the image classification problem for a large number of categories. Among them, methods based on tree-based representations achieve good trade-off between accuracy and test time efficiency. While focusing on learning a tree-shaped hierarchy and the corresponding set of classifiers, most of them use a greedy prediction algorithm for test time efficiency. We argue that the dramatic decrease in accuracy at high efficiency is caused by the specific design choice of the learning and greedy prediction algorithms. In this work, we propose a classifier which achieves a better trade-off between efficiency and accuracy with a given tree-shaped hierarchy. First, we convert the classification problem as finding the best path in the hierarchy, and a novel branch-and-bound-like algorithm is introduced to efficiently search for the best path. Second, we jointly train the classifiers using a novel Structured SVM (SSVM) formulation with additional bound constraints. As a result, our method achieves improvement in accuracy at high efficiency compared to state-of-the-art greedy "tree-based" methods dataset, respectively. This work was presented at the ICCV conference in December 2013 [31]

Progress 6: ***A Unified Framework for Object Detection, 3D Pose Estimation, and Sub-category Recognition [32]***. Object detection, 3D pose estimation, and sub-category recognition are usually highly correlated tasks. However, these tasks are typically addressed independently from each other because of the huge space of parameters when modeled jointly. To jointly model all of these tasks, we propose a coarse-to-fine hierarchical representation, where each level of the hierarchy represents objects at a different level of granularity. The hierarchical representation prevents performance loss, which is often caused by the increase in the number of parameters (as we consider more tasks to model), and the joint modeling enables resolving ambiguities that exist in independent modeling of these tasks. We augment PASCAL3D – a state-of-the-art large scale 3D object dataset – with annotations for these tasks and show that our hierarchical model is effective in joint modeling of object detection, 3D pose estimation, and sub-category recognition. This work has been submitted to NIPS 2014 [31].

Publications referenced appeared or submitted over grant period 7/1/09-06/30/14

Published in previous report periods

[1] K. Carter, R. Raich, W. Finn, A.O. Hero, “Information-Geometric Dimensionality Reduction,” IEEE Signal Processing Magazine, vol. 28, no. 2, pp. 89-99, Mar. 2011.

[2] Xu Chen and A.O. Hero, "Video indexing and retrieval using Fisher information non-linear embedding (FINE)," SPIE Electronic Imaging Conference, San Jose, Jan. 2011.

[3] X, Chen, S. Savarese and A.O. Hero, "Multimodal Video Indexing Using Directed Information ," IEEE Transactions on Multimedia, vol 14, no 1, pp. 3-16, Feb 2012. Preprint posted electronically on IEEE Xplore on Sept 5, 2011.

[4] L. Mei, J. Liu, AO Hero, S. Savarese, "Robust object pose estimation via statistical manifold modeling," Proceedings of 13th Intl Conf on Computer Vision (ICCV), Barcelona, Nov. 2011.

[5] K. Sohn, D-Y Jung, H Lee, AO Hero, "Efficient learning of sparse, distributed, convolutional feature representations for object recognition," Proceedings of 13th Intl Conf on Computer Vision (ICCV), Barcelona, Nov. 2011.

[6] X. Chen, Z. Syed and A.O. Hero, "EEG spatial decoding with shrinkage regularized directed information assessment,” IEEE ICASSP, Kyoto, April 2012.

[7] Xu Chen, Yilun Chen and Alfred Hero, "Shrinkage Fisher Information Embedding of High Dimensional Feature Distributions", Proceedings of Asilomar Conference, Pacific Grove, Nov 2011.

[8] S.-J. Hwang, S. Damelin, A.O. Hero, "Shortest path through random points." Submitted to the Annals of Applied Probability. Available on ArXiv, 31 Jan 2012 arXiv:1202.0045.

[9] M. Sun, M. Telaprolu, H. Lee, S. Savarese, “An Efficient Branch-and-Bound Algorithm for Optimal Human Pose Estimation,” IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2012.

[10] M. Sun, M. Telaprolu, H. Lee, S. Savarese, “Efficient and Exact MAP Inference using Branch and Bound,” 15th International Conference on Artificial Intelligence and Statistics (AISTATS), 2012.

[11] Y. Xiang and S. Savarese, “Estimating the Aspect Layout of Object Categories,” IEEE Conference on

Computer Vision and Pattern Recognition (CVPR), 2012.

[12] K.S. Xu, M. Kliger, AO Hero, "A regularized graph layout framework for dynamic network visualization," J. Data Mining and Knowledge Discovery, Volume 27, Issue 1, pp. 84-116, July 2013. Available as arXiv:1202.6042

[13] K. Todros and A.O. Hero, "On Measure Transformed Canonical Correlation Analysis," IEEE Trans. on Signal Processing, vol 60, no. 9, pp. 4570-4585, Sept. 2012. Available as arXiv:1111.6308.

[14] K.-J. Hsiao, K. S. Xu, J. Calder and A. O. Hero, "Multi-criteria Anomaly Detection using Pareto Depth Analysis", Proc. of Neural Information Processing Systems (NIPS), Dec 2012. This paper and its supplements were aggregated as arXiv:1110.3741 .

[15] K. Sricharan and A. O. Hero. "Ensemble weighted kernel estimators for multivariate entropy estimation", Proc. of Neural Information Processing Systems (NIPS), Dec 2012.

[16] J. Calder, S. Esedoglu and A. O. Hero III, "A Hamilton-Jacobi equation for the continuum limit of non-dominated sorting", to appear in SIAM Journal on Mathematical Analysis (SIMA). Preprint at arXiv:1302.5828, Feb 2013

[17] B. Kim, S. Xu and S. Savarese, “Accurate Localization of 3D Objects from RGB-D Data using Segmentation Hypotheses,” IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2013 .

[18] Y. Xiang and S. Savarese, “Enhancing object detection by 3D occlusion reasoning,” IEEE International Conference in Computer Vision (ICCV), 2013

[19] B. Kim, P. Kholi and S. Savarese, “3D Scene Understanding by Voxel-CRF,” IEEE International Conference in Computer Vision (ICCV), 2013

[20] K. Sricharan, D. Wei, and A.O. Hero, "Ensemble estimators for multivariate entropy estimation," IEEE Trans on Information Theory, Vol 59, No 7, pp. 4374-4388, July 2013. Preprint at arxiv:1203.5829.

Published or submitted in current report period (8/1/13-6/30/14):

[21] K.S. Xu, M. Kliger, AO Hero, "Adaptive evolutionary clustering," J. Data Mining and Knowledge Discovery, Volume 29, Issue 2, pp. 304-336, 2014. Available as arXiv:1104.1990

[22] P.-Y. Chen and A.O. Hero, "Local Fiedler Vector Centrality for Detection of Deep and Overlapping Communities in Networks," Proc. of IEEE Conf. on Acoustics, Speech and Signal Processing (ICASSP) 2014. Florence Italy, May 2014. ARO-databases.

[23] P.-Y. Chen and A.O. Hero, "Node Removal Vulnerability of the Largest Component of a Network," Proceedings of IEEE GlobalSIP Austin TX Dec 2013.

[24] J. Calder, S. Esedoglu, A. O. Hero, "A PDE-based approach to non-dominated sorting," available as arxiv:1320.2498(Oct 2013). Submitted to SIAM Numerical Analysis.

[25] J. Calder, S. Esedoglu and A.O. Hero, "A continuum limit for non-dominated sorting,” Conference on Information Theory and its Applications (ITA), San Diego, Feb 2014.

[26] K.J. Hsiao, J. Calder and A.O. Hero, "Pareto-depth for multiple-query image retrieval," Submitted. Available as arxiv:1402.5176 (.html) . 2014.

[27] K.-J. Hsiao, J. Kulezsa and A.O. Hero, "Social Collaborative Retrieval," IEEE Journal on Selected Topics in Signal Processing, Vol. 8, No. 4, pp. 680 - 689, 2014. Available as arxiv:1404.2342 (.html)

[28] X. Chen, A. Hero, S. Saverese, "Shrinkage Optimized Directed Information using Pictorial Structures for Action Recognition," Technical Report, 2014. Available as arxiv:1404.3312 (.html) .

[29] X. Chen, S. Syed, and AO Hero, "EEG Spatial Decoding and Classification with Logit Shrinkage Regularized Directed Information Assessment (L-SODA)." Technical Report, 2014. Available as arXiv:1404.0404 (.html) .

[30] K. Todros and A.O. Hero, "Robust Measure Transformed MUSIC for DOA Estimation," Proc. of IEEE Conf. on Acoustics, Speech and Signal Processing (ICASSP) 2014.

[31] M. Sun, W. Huang, and S. Savarese, *Find the Best Path: an Efficient and Accurate Classifier for Image Hierarchies*, Proceedings of the International Conference in Computer Vision (ICCV) 2013.

[32] R. Mottaghi, S. Savarese, *An Unified Framework for Object Detection, 3D Pose Estimation, and Sub-category Recognition*, NIPS (submitted) 2014

DATA REQUIRED

(1) Submissions or publications under ARO sponsorship during this reporting period. List the title of each and give the total number for each of the following categories:

(a) Papers published in peer-reviewed journals: 3

K.S. Xu, M. Kliger, AO Hero, "Adaptive evolutionary clustering," J. Data Mining and Knowledge Discovery, Volume 29, Issue 2, pp. 304-336, 2014. Available as arXiv:1104.1990

J. Calder, S. Esedoglu, A. O. Hero, "A PDE-based approach to non-dominated sorting," to appear in SIAM Numerical Analysis. Available as arxiv:1320.2498(Oct 2013).

K.-J. Hsiao, J. Kulezsa and A.O. Hero, "Social Collaborative Retrieval," IEEE Journal on Selected Topics in Signal Processing, Vol. 8, No. 4, pp. 680 - 689, 2014. Available as arxiv:1404.2342 (.html)

(b) Papers published in non-peer-reviewed journals: 0

(c) Presentations

i. Presentations at meetings, but not published in Conference Proceedings 4

Alfred Hero, "Small sample community detection in massive data sets," Plenary talk, IEEE CAMSAP Workshop, St Martins. Dec 2013.

Alfred Hero, "Spatio-temporal graphical models for high dimensional network data," Keynote talk, Network Theory Symposium, IEEE GlobalSIP Conference, Austin TX., Dec 2013.

Alfred Hero, "Sparsity regularized image reconstruction," Quantitative Non-Destructive Evaluation (QNDE), Keynote talk, Boise ID, July 2014.

Alfred Hero, "Correlation mining in large networks with limited samples," Keynote talk, IEEE International Telecommunications Symposium, Sao Paolo Brazil. Aug. 2014.

Silvio Savarese, “Perceiving the 3D world”, invited talk at the Large Scale Visual Commerce workshop**, in** conjunction of ICCV 2013, Australia, December 2013

ii. Non-Peer-Reviewed Conference Proceeding publications (other than abstracts): 1
J. Calder, S. Esedoglu and A.O. Hero, "A continuum limit for non-dominated sorting,” Conference on Information Theory and its Applications (ITA), San Diego, Feb 2014.

iii. Peer-Reviewed Conference Proceeding publications (other than abstracts): 5
P.-Y. Chen and A.O. Hero, "Local Fiedler Vector Centrality for Detection of Deep and Overlapping Communities in Networks," Proc. of IEEE Conf. on Acoustics, Speech and Signal Processing (ICASSP) 2014. Florence Italy, May 2014. ARO-databases.

P.-Y. Chen and A.O. Hero, "Node Removal Vulnerability of the Largest Component of a Network," Proceedings of IEEE GlobalSIP Austin TX Dec 2013.

K. Todros and A.O. Hero, "Robust Measure Transformed MUSIC for DOA Estimation," Proc. of IEEE Conf. on Acoustics, Speech and Signal Processing (ICASSP) 2014.

M. Sun, W. Huang, and S. Savarese, *Find the Best Path: an Efficient and Accurate Classifier for Image Hierarchies*, Proceedings of the International Conference in Computer Vision (ICCV) 2013.

R. Mottaghi, S. Savarese, *An Unified Framework for Object Detection, 3D Pose Estimation, and Sub-category Recognition*, NIPS (submitted) 2014

(d) Manuscripts 1
J. Calder, S. Esedoglu, A. O. Hero, "A PDE-based approach to non-dominated sorting," available as arxiv:1320.2498(Oct 2013). Submitted to SIAM Numerical Analysis.

(e) Books
(f) Honors and Awards
Lifetime career award: IEEE Signal Processing Society Technical Achievement Award, given at the 2014 Intl. Conf on Acoustic, Speech, and Signal Processing, Florence Italy. May 2014.

Best paper award: IEEE CAMSAP 2013 Best Student Paper Competition, awarded 2nd place for a paper coauthored with my former student Zhaoshi Meng and former post-docs Dennis Wei and Ami Wiesel entitled “Marginal Likelihoods for Distributed Estimation of Graphical Model Parameters,” IEEE Computational Advances in Multi-Sensor Adaptive Processing workshop, St Martins. Dec 2013.

Best paper award: IEEE ICIP 2013 Best Paper Award, for a paper co-authored with former student Paul Shearer and colleague Anna Gilbert entitled “Correcting Camera Shake by Incremental Sparse Edge Approximation,” at the 2013 IEEE Intl. Conf. on Image Processing, Melbourne Australia. Sept. 2013.

Plenary talk: “Small sample community detection in massive data sets,” IEEE CAMSAP Workshop, St Martins. Dec 2013.

Keynote: “Resource constrained adaptive sensing,” New Sensing and Statistical Inference Methods Symposium, IEEE GlobalSIP Conference, Austin TX. Dec 2013.

Keynote: “Spatio-temporal graphical models for high dimensional network data,” Network Theory Symposium, IEEE GlobalSIP Conference, Austin TX., Dec 2013.

Keynote: "Sparsity regularized image reconstruction," Quantitative Non-Destructive Evaluation (QNDE), Boise ID, July 2014.

Keynote: "Correlation mining in large networks with limited samples," IEEE International Telecommunications Symposium, Sao Paolo Brazil. Aug. 2014.

Plenary: "Correlation mining for imaging and multidimensional signal processing," IEEE Intl Conference on Image Processing, Paris France. Oct. 2014

Alfred Hero was invited to give 6 plenary lectures including the following:

1. "Small sample community detection in massive data sets," IEEE CAMSAP Workshop, Dec 2013.
2. "Resource constrained adaptive sensing," New Sensing and Statistical Inference Methods Symposium, IEEE GlobalSIP Conference, Dec 2013.
3. "Spatio-temporal graphical models for high dimensional network data," Network Theory Symposium, IEEE GlobalSIP Conference, Dec 2013.
4. "Information-driven multimodality fusion," AFRL/UES Workshop on Data Fusion for the Detection of Rare and Anomalous Events, Dec 2012."
5. "Graphical modeling for high dimensional data analysis," (Keynote 1)" Solar Information Processing Workshop (SIP) VI, MSU Bozeman, Aug. 14 2012.
6. "Learning with entropic graphs," (Keynote Solar Information Processing Workshop (SIP) VI, MSU Bozeman, Aug. 15 2012.

Alfred Hero won a Notable Paper award for his work on graphical models from AISTATS 2013 for the paper: Z. Meng, D. Wei, A. Wiesel, A. Hero, "Distributed Learning of Gaussian Graphical Models via Marginal Likelihoods," AISTATS Scottsdale AZ. April 2013.

Alfred Hero was awarded the University of Michigan Rackham Distinguished Faculty Achievement Award in 2011.

(g) Title of Patents Disclosed during the reporting period
(h) Patents Awarded during the reporting period

(2) Student/Supported Personnel Metrics for this Reporting Period (name, % supported, %Full Time Equivalent (FTE) support provided by this agreement, and total for each category):

(a) Graduate Students
Liang Mei, 50% FTE, EE: systems, PhD candidate
Min Sun, 50% FTE, EE: systems, PhD candidate
Yu Xiang, 50% FTE, EE: systems, PhD candidate
Dae Yon Jung, 50% FTE, EE: systems, PhD candidate
Ko-Jen Hsiao, 50% FTE, EE: system PhD candidate
Zhaoshi Meng: 50% FTE, EE: systems, PhD candidate
Yu-Wei Chao: 50% FTE, EE: system PhD candidate
Jinyoung Hwang: 50% FTE, EE: systems, PhD candidate
Sung Jin Hwang: 50% FTE, EE: systems, PhD candidate
Anush Mohan: 50% FTE, EE: systems, PhD candidate

(b) Post Doctorates
Sung Jin Hwang: 100% FTE
Xu Chen: 50% FTE

John Alexander Kulesza: 50% FTE
Greg Newstadt: 100% FTE
Koby Todros; 100% FTE

(c) Faculty
Alfred Hero
Silvio Savarese

(d) Undergraduate Students
(e) Graduating Undergraduate Metrics (funded by this agreement and graduating during this reporting period):
i. Number who graduated during this period
ii. Number who graduated during this period with a degree in science, mathematics, engineering, or technology fields
iii. Number who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields
iv. Number who achieved a 3.5 GPA to 4.0 (4.0 max scale)
v. Number funded by a DoD funded Center of Excellence grant for Education, Research and Engineering 0
vi. Number who intend to work for the Department of Defense
vii. Number who will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields
(f) Masters Degrees Awarded (Name of each, Total #)
(g) Ph.D.s Awarded (Name of each, Total #) 3
Sung Jin Hwang, EE: systems, PhD August 2012
Min Sun, EE: systems, PhD May 2013
Ko-Jen (Mark) Hsiao, EE: systems, PhD June 2014.

(h) Other Research staff (Name of each, FTE % Supported for each, Total % Supported)
Yue Hou: (Temp) 10% FTE
Akshay Kumar Jain Pokarma: 10% FTE
Taoran Yan: (Temp) 5% FTE
Anuj Chandawalla: (Temp) 5% FTE
Chang Wang: (Temp) 5% FTE

(3) “Technology transfer” (any specific interactions or developments which would constitute technology transfer of the research results). Examples include patents, initiation of a start-up company based on research results, interactions with industry/Army R&D Laboratories or transfer of information which might impact the development of products.

Alfred Hero visited ARL in June 2014 where he met with ARL researchers to discuss, among other things, research under this grant. ARL researchers with whom Al Hero interacted included: Lance Kaplan, Brian Sadler, and Nasser Nasrabadi.

The Pareto multiple query image retrieval software implementing the method reported in publication [26] was transitioned to ARL and is under evaluation.

Supported student Brandon Oselio did an internship at ARL under Lance Kaplan in summer 2014.

Alfred Hero visited Army Research Laboratory for one day in Feb 2013. He had discussions with Lance Kaplan, Brian Sadler, Nasser Nasrabadi, Terry Moore and Tien Pham on topics relevant to this project.

Two of Alfred Hero's PhD students (Brandon Oselio and Ted Tsiligaridis) visited ARL as interns in summer 2013.

Alfred Hero has had several meetings with ARL researchers Brian Sadler, Laurel Sadler and Robert Winkler on designing a human factors experiment at ARL using the Pareto frontier search engine (https://dl.dropboxusercontent.com/u/13611327/paretoretrievalgui.zip) developed under this project.

Alfred Hero helped Liyi Dai organize a Government Panel of DoD researchers and research managers in Ann Arbor at the IEEE Statistical Signal Processing Workshop (A Hero was General Chair).

Alfred Hero visited Army Research Laboratory for one day in January 2012. He had discussions with Lance Kaplan, Brian Sadler, Nasser Nasrabadi, Terry Moore on topics relevant to this project.

Two of Alfred Hero's PhD students visited ARL as interns in summer 2012.

Alfred Hero met with ARL researchers Brian Sadler and Terry Moore at College Park during the FFT symposium held in the Dept of Mathematics at Univ of Maryland.

Alfred Hero organized an ARO sponsored workshop in April in Annarbor on Sensor Information Estimation and Exploitation with the help of Army research and development center researcher Donald Waagen.

Alfred Hero helped Liyi Dai organize a Government Panel of DoD researchers and research managers in Ann Arbor at the IEEE Statistical Signal Processing Workshop (A Hero was General Chair).