Preview of Award 1042998 - Final Project Report

Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1042998
Project Title:	ATD: Collaborative Research: Multiscale and Stochastic Methods for Inverse Source Problems and Signal Analysis
PD/PI Name:	Hao-Min Zhou, Principal Investigator
Recipient Organization:	Georgia Tech Research Corporation
Project/Grant Period:	10/01/2010 - 09/30/2014
Reporting Period:	10/01/2013 - 09/30/2014
Submitting Official (if other than PD\PI):	N/A
Submission Date:	N/A
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	N/A

Accomplishments

*** What are the major goals of the project?**

The main goals of this project are to develop and analyze several multi-scale and stochastic models and the efficient numerical methods for problems arising in image processing, inverse source problems and nonlinear and non-stationary signal analysis. It focuses on three topics: 1) developing efficient multiscale image processing algorithms for wavelet inpainting; 2) establishing new stochastic models and fast multi-resolution algorithms for inverse source problems and their applications in imaging science; and 3) exploring the iterative filtering techniques and instantaneous frequency analysis for nonlinear and non-stationary signals. The project also aims to train Ph.D students and postdoctoral scholars using the proposed research problems.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities: The PI presented his work at following conferences/workshops, and seminars;

- Summer school in mathematics, Zhejiang University, HangZhou, China, 7/3-7/19, 2014
- International Conference on Recent Advance in Dynamical Systems, Guilin, China, 6/1-6/4, 2014
- SIAM Conference on Imaging Science, Hong Kong, 5/12-5/14, 2014
- Applied math seminar, UC Irvine, 4/29, 2014
- Undergraduate math club, University of Georgia, Athens, Georgia, 4/2, 2014

- Applied math seminar, School of Mathematics, Peking University, Beijing, 3/24, 2014
- Workshop on stochastic differential equations, School of Mathematics and System Science, Chinese Academy of Sciences, Beijing, 3/15-3/26, 2014
- Dynamical system seminar, BYU, Provo, UT. 3/13, 2014
- NSF/DTRA/NGA 2014 Algorithm Workshop, Boulder, Co., 3/9-3/12, 2014
- MSRI workshop: Fluid Mechanics, Hamiltonian Dynamics, and Numerical Aspects of Optimal Transportation, 10/13-10/17, 2013
- Applied Math Seminar, Auburn University, 9/27/2013
- Applied Math Seminar, University of Georgia, Athens, 9/16/2013
- Copper County workshop on Numerical Analysis and Inverse Problems. Michigan Tech, Houghton, Michigan, 8/12-8/14, 2013
- International Congress of Chinese Mathematicians (ICCM), Taipei, 7/13/-7/20, 2013
- International Conference on Applied Inverse Problem, KAIST, Daejeon, S. Korea, 7/1-7/5, 2013
- Seminar, School of Mathematical Science, Chinese Academy of Sciences, Beijing, 6/27/2013
- Workshop on Dynamical Systems (2 one-hour long presentations), Zhejiang Normal University, Jinhua, 6/22/-6/24, 2013
- 2nd international conference on interdisciplinary applied and computational mathematics, Zhejiang University, Hang Zhou, 6/19-6/22, 2013
- Dynamical System Day, University of Sciences and Technology of China, Hefei, 6/13/2013
- Seminar, Center for Partial Differential Equations, East China Normal University, Shanghai, 6/10/2013
- Short course for undergraduate talent classes at mathematics department, Zhejiang University, Hang Zhou, 6/1-6/9, 2013
- Seminar, School of Technical Physics, Xidian University, Xi'an, 5/27, 2013
- International Conference on Approximation Theory and Applications, City University of Hong Kong, Hong Kong, 5/20-5/24, 2013
- 2013 Georgia Scientific Computing Symposium, at Georgia State University, Panelist. 2/23, 2013
- MBI Workshop on Mathematical Challenges in Biomolecular/Biomedical Imaging and Visualization. 2/18-2/22: BMI, Ohio State University, Columbus, Ohio
- IPAM Workshop on Adaptive Data Analysis and Sparsity. 1/27-2/2, 2013, IPAM, UCLA
- Colloquium, Department of Mathematics and Statistics, Georgia State University, 1/25, 2013
- NSF/DTRA/NGA, 2012 Algorithm workshop, 11/26-11/30, 2012, San Diego
- The Sixth International Conference on Recent Advances in Applied Dynamical Systems, Guang Zhou, China, June 24-28, 2012
- SIAM-SEAS, South-East Sectional Meeting, University of Alabama, Huntsville, Alabama, March 24-25, 2012
- The IV Developers Workshop on the Conley-Morse Database Project, Kauai, Hawaii, March 19-22, 2012
- Applied and Computational Mathematics Seminar, Department of Mathematics, Purdue University, March 9, 2012
- The International Conference on Scientific Computing in Honor of Professor Tony Chan's 60th birthday, Hong Kong, Jan 4-7, 2012
- Colloquium, Department of Mathematics and Statistics, Air Force Institute of Technology, Dayton, OI, Nov. 5, 2011
- The Conference on Applied Harmonic Analysis and Multiscale Computations, University of Alberta, Edmonton, Alberta, Canada, July 24-28, 2011
- The International Conference on Applied Mathematics, Zhejiang University, Hang Zhou, China, June 17-22, 2011
- Colloquium, School of Applied Technical Physics, Xidian University, Xi'an, China, June 24, 2011

- Dynamical System Seminar, University of Science and Technology of China, Hefei, China, June 16, 2011
- DTRA/NSF Algorithm Workshop, Boston, June 6-9, 2011
- Seminar in the School of Technical Physics, Xidian University, Xi'an, China, 6/22, 2011
- The International Conference on Interdisciplinary Applied and Computational Mathematics, Zhejiang University, HangZhou, China, June 17-22, 2011
- Mathematics Seminar, University of Science and Technology of China, Hefei, June 16, 2011
- DTRA/NSF Algorithm Workshop, Boston, June 7-9, 2011
- The Forth International Conference on Computational Harmonic Analysis, City University of Hong Kong, Hong Kong, May 23-27, 2011
- Workshop on Applied Harmonic Analysis and Approximation Theory, Sun Yat-sen University, Guang Zhou, China, May 20-21, 2011
- AMS Spring Central Section Meeting. University of Iowa. Iowa City, Iowa. March 18-20, 2011
- Georgia Scientific Computing (GSC) Symposium, Emory University, Atlanta, Feb. 12, 2011
- Applied Math Seminar, Peking University, Beijing, Dec 24, 2010
- Dynamical Syetem Seminar, Shanghai Jiaotong University, Shanghai, China, Dec. 20, 2010
- Mathematics Department Seminar, Shanghai Normal University, Shanghai, China, Dec. 17, 2010
- Mathematics Department Seminar, University of Science and Technology of China (USTC), Hefei, Dec. 14, 2010
- The Second Workshop on Interdisciplinary Applied and Computational Mathematics, Zhejiang University, HangZhou, China, Dec. 2-5, 2010
- Mathematics Seminar, Hong Kong Baptist University, Hong Kong, Nov 22, 2010
- Math Colloquium, The Chinese University of Hong Kong, Nov. 19, 2010
- Mathematics and Computational Science Seminar, Sun Yat-Sen University, GuangZhou, China, Nov 18, 2010
- Faculty of Science and Technology Seminar, University of Macau, China, Nov 15, 2010
- Workshop on Some Approximation Approaches for Data Processing, Zhejiang University, HangZhou, China, October 30-31, 2010

The PI participated in organizing the following meetings and seminars:

- The Applied and Computational Mathematics Seminar, School of Mathematics, Georgia Tech
- Mini-symposium on recent advance on imaging sciences, 2nd international conference on interdisciplinary applied and computational mathematics, Zhejiang University, Hang Zhou, 6/19-6/22, 2013
- IPAM Workshop on Adaptive Data Analysis and Sparsity. 1/27-2/2, 2013, IPAM, UCLA
- International Conference on the Frontier of Computational and Applied Mathematics, in honor of Professor Tony Chan on his 60th birthday, IPAM, UCLA, June 8-10, 2012

The PI visited, or is scheduled to visit the following institute for research collaborations:

- University of Texas at Austin, collaboration with Professor Engquist, 10/14-10/16, 2012, and 4/4-4/5, 2013
- Visit: Naval Surface Warfare Center, Panama City, FL. July 13-15, 2011
- Visit: Montana State University, Bozeman, MT, August 9-12, 2011.

Specific Objectives: The PI continues his study of problems related to wavelets and PDE techniques in signal and image processing and stochastic differential equations in this report period. The

Significant Results: following are the different problems that he has been working on in the past 4 years.

- Nonlinear signal decomposition strategies and instantaneous frequency analysis
- Efficient algorithms for wavelet inpainting
- Total variation (TV) models and numerical methods for optical imaging
- Stochastic inverse problem, and its computations
- E-JOB for Shortest path problems and applications in robotics
- Random teleportation on graphs for global optimization and ranking

A detailed description of each problem area is attached.

Key outcomes or Other achievements:

*** What opportunities for training and professional development has the project provided?**

During this period of time, the PI supervised 5 Ph.D students: 3 Ph.D. students in mathematics and 2 Ph.D students in computational science and engineering (CSE) at Georgia Tech. Among them, Dr. Ke Yin (math, now postdoc at UCLA) and Dr. Jingfang Liu (CSE, now at Oracle) graduated in the spring and summer of 2013 respectively. Dr. Jun Lu (math, now at Wells Fargo) graduated in the spring of 2014. Currently, he co-advises Mr. Wuchen Li (4th year math Ph.D student) with Professor Luca Dieci (math) working on stochastic differential equations and their applications in optimal control, and co-advises Mr. Yichen Wang (CSE, 2nd year Ph.D student) with Professor Hongyuan Zha (CSE) working on diffusion on graphs. He mentored two postdoctoral scholars, Dr. Xiaojing Ye and Dr. Antonio Cicone, in the School of Mathematics at Georgia Tech. Now Dr. Xiaojing Ye is a tenure track assistant professorship at Georgia State University, and Dr. Cicone is with L'Aquila University, Italy. Currently, the PI is mentoring three postdoctoral scholars, Drs. Manuela Manetta, Chunmei Wang and Seong Jun Kim. And a fourth postdoc, Dr. Christina Frederick will join his research team in Jan 2015. He also hosted a visiting Ph.D student, Mr. Feng Zhou from Sun Yat-sen University, China at Georgia Tech for a year (2013-2014), and an intern student, Mr. Philip Polack from Mines Paris Tech, France for 5 months in 2014. He is actively recruiting more students and postdocs in the coming academic year.

*** How have the results been disseminated to communities of interest?**

The results obtained by the PI, his research group and collaborators have been disseminated by publishing journal papers, conference proceedings, conference presentations, seminars, and conference posters.

Products

Books

Book Chapters

S. N. Chow, T. S. Yang and H. M. Zhou (2013). Global Optimizations by Intermittent Diffusion. *Chaos, CNN, Memristors and Beyond: A Festschrift for Leon Chua* Adamatzky Andrew, et al.. World Scientific Publishing Co. Pte. Ltd. 466-279. Status = PUBLISHED; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes ; ISBN: 9789814434805.

Conference Papers and Presentations

Haomin Zhou (2013). *Adaptive Iterative Filtering Method for Signal Decompositions and Instantaneous Frequency analysis*. Dynamical System Day. Hefei, China. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2013). *An Efficient Numerical Methods for Inverse Source Problems with Applications in Fluorescence Tomography*. Copper County workshop on Numerical Analysis and Inverse Problems. Houghton, Michigan. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2013). *An Orthogonal Solution and Kernel Correction Algorithm for Inverse Source Problems with Applications in Fluorescence Tomography*. Second international conference on interdisciplinary applied and computational mathematics. Hang Zhou, China. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2013). *An Orthogonal Solution and Kernel Correction Algorithm for Inverse Source Problems with Applications in Fluorescence Tomography*. MBI Workshop on Mathematical Challenges in Biomolecular/Biomedical Imaging and Visualization. olumbus, Ohio. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2012). *An efficient algorithm for finding the shortest path by solving initial value problems of ODE's,*. The International Conference on Scientific Computing in Honor of Professor Tony Chan's 60th birthday. Hong Kong. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2011). *Cross-Channel Anisotropic Diffusion for Color Image Denoising*. Workshop on Applied Harmonic Analysis and Approximation Theory. Sun Yat-sen University, Guang Zhou, China. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2010). *Cross-Channel Anisotropic Diffusion for Color Image Denoising*. Workshop on Some Approximation Approaches for Data Processing. Zhejiang University, HangZhou, China. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2011). *Efficient Methods for Forward and Inverse Stochastic Source Problems of Helmholtz Equation and Applications*. Georgia Scientific Computing (GSC) Symposium. Emory University, Atlanta, GA. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2010). *Efficient Methods for Forward and Inverse Stochastic Source Problems of Helmholtz Equation and Applications,*. The Second Workshop on Interdisciplinary Applied and Computational Mathematics,. Zhejiang University, HangZhou, China. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2011). *Efficient Numerical Methods for Forward and Inverse Stochastic Helmholtz Equations and Applications,*. AMS Spring Central Section Meeting. University of Iowa. Status = OTHER; Acknowledgement of Federal Support = No

Haomin Zhou (2013). *Evolving Junctions on Obstacle Boundaries (E-JOB) method for the shortest path problems, a stochastic differential equations (SDE) approach*. International Congress of Chinese Mathematicians (ICCM). Taipei. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2011). *Fast Numerical Methods for Forward and Inverse Helmholtz Equations with Stochastic Sources and Applications*. The Fourth International Conference on Computational Harmonic Analysis. City University of Hong Kong, Hong Kong. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2012). *Finding the Shortest Path by Evolving Junctions on Obstacle Boundaries (E-JOB): a SDE Strategy*. NSF/DTRA/NGA 2012 Algorithm Workshop. San Diego, California. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2012). *Finding the shortest path by evolving junctions on obstacle boundaries (E-JOB)*. The Sixth International Conference on Recent Advances in Applied Dynamical Systems. Guang Zhou, China. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2012). *Finding the shortest path by solving initial value problems of ODE's*. SIAM-SEAS, South-East Sectional Meeting. University of Alabama, Huntsville, Alabama. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2012). *Fokker-Planck equations for a free energy functional and Markov processes on graphs*. The IV Developers Workshop on the Conley-Morse Database Project. Kauai, Hawaii. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2011). *Intermittent Diffusion, Conley-Markov Matrix and Global Optimization*. The International Conference on Applied Mathematics. Hang Zhou, China. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2013). *Iterative Filtering Methods and Instantaneous Frequency Analysis*. IPAM Workshop on Adaptive Data Analysis and Sparsity. Los Angeles, California. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2011). *Iterative Filters and Instantaneous Frequency Analysis*. Conference Applied Harmonic Analysis and Multiscale Computations. University of Alberta, Edmonton, Canada. Status = OTHER; Acknowledgement of Federal Support = Yes

H. M. Zhou (2011). *Iterative Filters for EMD and Instantaneous Frequency Analysis*. DTRA/NSF Algorithm Workshop. Boston, MA. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2013). *Local Adaptive Iterative Filtering Method for Signal Decompositions and Instantaneous Frequency*

analysis. International Conference on Approximation Theory and Applications. Hong Kong. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2013). *Orthogonal Solution and Kernel Correction Algorithms for Inverse Source Problems*. International Conference on Applied Inverse Problem. Daejeon, S. Korea. Status = OTHER; Acknowledgement of Federal Support = Yes

Haomin Zhou (2013). *SDEs, Intermittent Diffusions, Instantaneous Frequency Analysis*. Workshop on Dynamical Systems. Jinhua, China. Status = OTHER; Acknowledgement of Federal Support = Yes

Inventions

Journals

A. Behrooz, H. M. Zhou, A. Eftekhar and A. Adibi (2012). Total Variation Regularization for 3D Reconstruction in Fluorescence Tomography: Experimental Phantom Studies. *Applied Optics*. 51 (34), 8216-8227. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

F. Zhou, L. J. Yang, H. M. Zhou and L. H. Yang (2014). Optimal Averages for Nonlinear Signal Decompositions - Another Alternative for Empirical Mode Decomposition. *Signal Processing*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

G. Bao, S. N. Chow, P Li and H. M. Zhou (2014). An Inverse Random Source Problem for the Helmholtz Equation. *AMS Mathematics of Computation*. 83 215-233. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

S. -N. Chow, X. Ye and H. M. Zhou (2014). Potential Induced Random Teleportation on Finite Graphs. *Computational Optimization and Applications.*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

S.-N Chow, J. Lu and H. M. Zhou (). The Shortest Path Amid 3-D Polyhedral Obstacles. *SIAM, Multiscale Modeling and Simulations*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

S.-N. Chow, J. Lu, and H. M. Zhou (2013). Fast Numerical Methods Based on SDES for Several Problems Related to the Shortest Path. *Methods and Application of Analysis*. 20 (4), 353-364. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

S.-N. Chow, J. Lu, and H. M. Zhou (2013). Finding the shortest path by evolving junctions on obstacle boundaries (E-JOB): An initial value ODE's approach. *J. Applied and Computational Harmonic Analysis*. 35 (1), 165-176. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

S.-N. Chow, K. Yin, H. M. Zhou, and A. Behrooz (2013). Solving Inverse Source Problems by the Orthogonal Solution and Kernel Correction Algorithm (OSKCA) with Applications in Fluorescence Tomography. *nverse Problem and Imaging*. 8 (1), 79-102. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

S.-N. Chow, W. Huang, Y. Li and H. M. Zhou (2011). A Free Energy Based Mathematical Study for Molecular Motors. *Regular and Chaotic Dynamics*. 16 (1-2), 117-127. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

S.-N. Chow, W. Huang, Y. Li and H. M. Zhou (2012). Fokker-Planck Equations for a Free Energy Functional or Markov Process on a Graph. *Archive for Rational Mechanics and Analysis*. 203 (3), 969-1008. Status = PUBLISHED; Acknowledgment of Federal Support = Yes

S.-N. Chow, W. Li, Z. Liu and H. M. Zhou (2012). A Natural Order in Dynamical Systems Based on Conley-Markov Matrices. *Journal of Differential Equations*. 252 (4), 3116-3141. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

X. Ye and H. M. Zhou (2013). Fast Total Variation Wavelet Inpainting via ApproximatedPrimal-Dual Hybrid Gradient (PDHG). *Inverse Problems and Imaging*. 7 (3), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Products

Other Publications
A. Behrooz, H. M. Zhou, A. Eftekhar and A. Adibi (2011). *Fast Total Variation Regularization for Higher Resolution in Fluorescence Tomography: A Split Bregman Iteration Approach*. Proceedings of the IEEE Photonics Conference (the 24th Annual Photonics Society Meeting). Status = PUBLISHED; Acknowledgement of Federal Support = No

A. Behrooz, H. M. Zhou, A. Eftekhar and A. Adibi (2011). *Toward robust high resolution fluorescence tomography: a hybrid row-action edge preserving regularization*. Optical Tomography and Spectroscopy of Tissue IX. Proceedings of the SPIE, Volume 7896. Status = PUBLISHED; Acknowledgement of Federal Support = No

Patents

Technologies or Techniques

Thesis/Dissertations
Jingfang Liu. *Adaptive Iterative Filtering for Nonlinear Signal Analysis and Applications*. (2013). Georgia Institute of Technology. Acknowledgement of Federal Support = No

Jun Lu. *Method of Evolving Junctions: A New Approach to Path Planning and Optimal Control*. (2014). Georgia Institute of Technology. Acknowledgement of Federal Support = No

Ke Yin. *New Algorithms for Solving Inverse Source Problems in Imaging Techniques*. (2013). Georgia Institute of Technology. Acknowledgement of Federal Support = No

Websites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Zhou, Hao-Min	PD/PI	2
Cicone, Antonio	Postdoctoral (scholar, fellow or other postdoctoral position)	9
Li, Wuchen	Graduate Student (research assistant)	5
Liu, Jingfang	Graduate Student (research assistant)	5
Lu, Jun	Graduate Student (research assistant)	5
Polack, Philip	Graduate Student (research assistant)	5

Full details of individuals who have worked on the project:

Hao-Min Zhou
Email: hmzhou@math.gatech.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Responsible for the overall scientific and technical direction of the project.

Funding Support: none

International Collaboration: Yes, Hong Kong, Norway

International Travel: Yes, Hong Kong - 0 years, 1 months, 4 days; China - 0 years, 0 months, 18 days; Korea, Republic Of - 0 years, 0 months, 4 days; Taiwan - 0 years, 0 months, 9 days

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Antonio Cicone
Email: acicone3@math.gatech.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 9

Contribution to the Project: working on nonlinear signal decompositions and applications

Funding Support: none

International Collaboration: No
International Travel: No

Wuchen Li
Email: wli83@math.gatech.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 5

Contribution to the Project: working on stochastic oscillators and optimal control problems

Funding Support: None

International Collaboration: No
International Travel: No

Jingfang Liu
Email: jliu74@math.gatech.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 5

Contribution to the Project: She worked on Iterative filtering methods and theory for nonlinear and non-stationary signal analysis with applications in differential equations.

Funding Support: None

International Collaboration: No
International Travel: No

Jun Lu
Email: jlu39@math.gatech.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 5

Contribution to the Project: Working on stochastic differential equations with applications in path planning, optimal control.

Funding Support: None

International Collaboration: No
International Travel: No

Philip Polack
Email: philip.polack@mines-paristech.fr
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 5

Contribution to the Project: Student internship, working on computational methods for optimal transportation equations

Funding Support: none

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?
Nothing to report.

Have other collaborators or contacts been involved? Yes

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The PI's research efforts have advanced several fronts in wavelets and PDE techniques in imaging science, networks, and large scale nonlinear data processing, and their applications in a variety of problems such as medical imaging and nonlinear data analysis. His studies in SDEs enrich the understandings in information propagation on graphs, in random inverse problems, and in global optimizations. In the past years, The PI performed peer reviews for more than a dozen journals in mathematics, computer science and engineering. He has been the managing editor for the journal Inverse Problems and Imaging (IPI), category editor for computing review (CR), and associate editor for sensing and imaging (SI).

What is the impact on other disciplines?

The PI's research has led to several on going collaborations with researcher from other disciplines, such as optics, robotics and control, and computer science. He is working with his collaborators on applications in areas of optics, especially biomedical imaging techniques such as fluorescent tomography, optimal path planning and optimal control for robots, and information propagations on large size networks with applications in social networks and public health. In the past 4 years, the PI has served on 20 Ph.D dissertation committees in the Schools of Mathematics, and Electric and Computer Engineering (ECE) at Georgia Tech as well as other universities in the US, Canada and Asia. He serves on many committees, including the computing committee and the executive committee for quantitative and computational finance (QCF) program at Georgia Tech.

What is the impact on the development of human resources?
Nothing to report.

What is the impact on physical resources that form infrastructure?
Nothing to report.

What is the impact on institutional resources that form infrastructure?
Nothing to report.

What is the impact on information resources that form infrastructure?
Nothing to report.

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?
Nothing to report.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Significant results

- Nonlinear signal decomposition strategies and instantaneous frequency analysis

The PI has been working to establish the mathematical foundation for empirical mode decomposition (EMD) like techniques for nonlinear and non-stationary signals. EMD, pioneered by N. Huang and his collaborators, is a recently emerged strategy designed to handle nonlinear and non-stationary signals that can be treated effectively by the classical signal analysis methods, such as wavelets, Fourier and statistical based methods. Working with his Ph.D student (in Computational Science and Engineering (CSE), graduated in 2013, now at Oracle) and his postdoc, Dr. Antonio Cicone (now at L'Aquilla University, Italy), the PI proposed a framework, named iterative filtering method, for nonlinear signal decompositions. The goal is to find a local, data adaptive and stable method to separate a signal into several components called intrinsic mode functions (IMFs), and each IMF can be analyzed more effectively by frequency analysis. It has been demonstrated in this project that the proposed adaptive local iterative filtering (ALIF) algorithm can achieve the goal. Moreover, they also proposed a new definition for the instantaneous frequency in order to obtain a completely local analysis for non-linear and non-stationary signals. Examples show that this decomposition really helps in both simulated data analysis and real world applications. The results obtained are collected in Ms. Liu's Ph.D thesis, and in three papers that will be submitted in the near future. In a recent study, they applied the ALIF algorithm to a problem to identify chemical or biological hazardous material contained in air plum through spectral analysis. The results were presented in the annual NSF/DTRA/NGA Algorithms Workshop in 2014.

Working together with another postdoc, Dr. Seong Jun Kim, the PI proposed a numerical method that combines the heterogeneous multi-scale method (HMM) and ALIF to compute the slow dynamics in a multi-scale system. The fundamental idea is to apply the ALIF algorithm to extract essential information, such as intermediate time scale and effective rate of change in slow variables, and then to use them in the HMM framework to compute the coarse scale behavior without fully resolving the fine scale solutions. Our numerical examples demonstrated that the new method has a number of advantages over the existing ones. 1) The effective rate of change for the slow dynamics is calculated as a result of the local solution decomposition by ALIF, and an effective ordinary differential equation (ODE) is obtained on-the-fly by analyzing the trend of IMFs. 2) ALIF can find hidden intermediate time scale, and the new method can treat multiple (> 2) time scale systems hierarchically. 3) The time-frequency analysis in ALIF allows us to identify some frequency related slow variables, such as the relative phase. This is especially useful for systems that slow variables are not known. The results related to this work are written in a paper in its final stage of revision.

Along this line of research, the PI and a visiting student, Mr. Feng Zhou from Sun Yat-sen University, proposed an alternative approach for nonlinear signal decompositions. They replace the average of upper and lower envelopes in the sifting procedure of EMD by a local average obtained solving a collection of locally defined variational optimization problems. Therefore an IMF can be produced by simply subtracting the average from the signal without iteration. They proved that the IMFs computed by this alternative strategy satisfy the two requirements proposed in the original EMD paper by Huang et al. Our numerical examples illustrate that the resulting

decomposition is convergent and robust against noise. The results of this study are reported in the paper that is submitted to the journal Signal Processing.

Moreover, the PI and collaborators from NSWC are working to extend the empirical mode decomposition (EMD) method to underwater sonar signals for better imaging results and target detections. The preliminary findings are quite promising.

- Efficient algorithms for wavelet inpainting

The wavelet inpainting is a mathematical problem that is closely related to the application of error concealment in telecommunications. The goal is to restore missing and damaged wavelet (or DCT) coefficients from known ones. The problem, and two mathematical models to solve it, were proposed by the PI and his collaborators in their earlier work. The models are total variation (TV) based, and can be solved by partial differential equations (PDEs). It is demonstrated that the models are very effective in filling in the missing or damaged wavelet coefficients. Especially, it can reconstruct the geometric features in the image. However, in the existing studies, the algorithms to compute the solutions of the models mainly use time marching, or multi-scale linearization strategies, which are less efficient. In a recent work by the PI and his postdoc, Dr. Xiaojing Ye (now assistant professor at Georgia State University), they successfully modified the primal-dual hybrid gradient (PDHG) algorithm and applied to the TV wavelet inpainting models for fast numerical solutions. This is the first known results of using PDHG for wavelet inpainting problem. In particular, as the original PDHG algorithm requires the orthogonality of encoding operators for optimal performance, they propose an approximated PDHG algorithm to tackle the non-orthogonality of Daubechies 7-9 wavelet, which is widely used in practice. They show that this approximated version essentially alters the gradient descent direction in the original PDHG algorithm, but eliminates its orthogonality restriction and retains low computation complexity. In addition, they prove that the sequences generated by the approximated PDHG algorithm always converge monotonically to an exact solution of the TV based image reconstruction models starting from any initial guess. They demonstrate that the approximated PDHG algorithm also works on more general image reconstruction problems with total variation regularizations, and analyze the condition on the step sizes that guarantees the convergence. This study is reported in a paper that is published in the Inverse Problems and Imaging, and the code developed in this project will be posted on the web for users to download.

- Total variation (TV) models and numerical methods for optical imaging

In a project joint with his Ph.D student, Dr. Ke Yin, who graduated in the spring of 2013 and now a postdoc at UCLA, and three engineers in the School of ECE at Georgia Tech, the PI continues to work on image reconstructions of fluorescence molecular tomography (FMT), a new in vivo imaging modality for medicine. Compared to other imaging modalities, such as CT or MRI, FMT has two distinct features: (1) FMT uses infrared light instead of X-rays, which is much less harmful. (2) FMT can be molecular specific, meaning it can trace targeted molecular in the tissue. This is preferred for early cancer detection and drug monitoring. Mathematically speaking, the goal in FMT is to reconstruct localization and quantification of the fluorescence distribution in tissues. It can be described by two couple parabolic equations with an unknown source. This is

a highly ill-conditioned problem as interior distribution must be extracted from a limited number of surface measurements. FMT is a topic rich of challenging questions in both mathematics and engineering. For example, to overcome the ill-posedness in the inverse problem, the existing literature uses L-2 based Tikhonov regularization, which can give reasonable approximations to the distribution. However, those methods show limitations in imaging resolutions and often smear the boundaries of interesting objects, which increase the difficult level in clinical usage. The PI and collaborators conducted investigations on different aspects of FMT. They proposed an algorithm that penalizes the total variation (TV) norm of the solution to preserve sharp transitions and high-frequency components in the reconstructed fluorescence map while overcoming ill-posedness. The performance of the proposed method in resolving fluorescent tubes inserted in a liquid tissue phantom imaged by a non-contact CW trans-illumination FMT system is studied and compared to conventional regularization schemes. It is observed that the proposed method performs better in resolving fluorescence inclusions at higher depths. The results have been reported in two proceeding papers in SPIE. A journal paper reporting complete simulation, experiments and analysis, is published by Applied Optics. The paper is also selected by the editors as a featured article published in the Virtual Journal for Biomedical Optics (VJBO).

In a more recent investigation, the PI and collaborators have proposed a novel framework called orthogonal solution and kernel correction algorithm (OSKCA) for FMT. The objectives include refining the image resolution, improving the boundary fitting, and speeding up the computations. To achieve the goals, they proposed the idea of finding the orthogonal solution (the minimal normal solution in some literature) to match the boundary measurements, and then use functions in the null space (kernel) of the differential operator to correct the orthogonal solution so that physical constraints, such as positivity and smoothness, are satisfied. The correction in the kernel will not impact the boundary fitting. The new OSKCA requires no artificial regularizations unless the unknown distribution carries an intrinsic regularity restriction. It doesn't possess inherited resolution limitation due to the artificial regularizations. In the numerical experiments, it shows superior performance in both resolution and robustness against the noise. The computational cost is greatly reduced (more than 10 times) too. The PI and his students have also investigated some theoretical problems in FMT. The framework is general, and should have no problem to extend to other inverse source problems in different applications. The results on this project are completed and a paper reporting the algorithm and applications has been accepted by Inverse Problem and Imaging.

- Stochastic inverse problem, and its computations

In the field of stochastic differential equations, the PI continues his collaborations with Prof. Chow form GT, Prof. Gang Bao of MSU and Prof. Peijun Li of Purdue University on stochastic inverse problems. For inverse problems, usually there are two major difficulties: the ill-posedness and the presence of many possible local minima. Compared to the classical inverse problems, stochastic inverse problems, referred to the inverse problems involving uncertainties, have substantially more difficulties due to the randomness and uncertainties. After their study on the Wiener Chaos Expansion (WCE) method for the inverse medium scattering problem with a stochastic source, which is to find a reconstruction of the refractive index of an inhomogeneous medium

from the scattering data, they considered a spatially stochastic inverse source problem, which is partially motivated by FMT studied in a different project. The main goal is to reconstruct the statistical distribution of the source function from boundary measurements of the radiation field, which is governed by the Helmholtz equations. First, they convert it into a two-point spatially stochastic boundary value problem, for which they have proved there exists a unique path-wise solution. Furthermore, they deduce an explicit formula for the solution by using the integrated solution method. Based on the analysis and solution formula, they propose a novel and efficient strategy, which only uses fast Fourier transforms (FFT), to reconstruct the statistical properties, such as the mean and the standard deviation or the variance, of the random source function from measurements at one boundary point in 1-D. Numerical examples demonstrate the validity and effectiveness of the proposed method. The paper reporting the results has been accepted by AMS Mathematics of Computation.

- E-JOB for Shortest path problems and applications in robotics

In a recent study with a Ph.D student, Mr. Jun Lu, and Prof. S. N. Chow, the PI proposes a new fast algorithm called Evolving Junctions on the Obstacle Boundaries (E-JOB) to find the globally shortest path connecting two points while avoiding obstacles in a region. This is a classical problem having numerous applications such as robot navigations. There is extensive literature on the subject. For 2-D polygonal obstacles, the solution can be computed efficiently by a $O(n \log n)$ algorithm based on the Dijkstra method. Here n is the number of vertices in the obstacles. However, this framework becomes NP-hard if the problem is 3-D. If the obstacles are not polygonal, then the combinatorial strategy can no longer be used. The best known method in this case is to solve a Eikonal equation, which is a PDE defined in the whole space. In this project, the PI and collaborators find a surprising simple way to determine the solution by evolving some junction points on the obstacle boundaries. The motions are given by simple ordinary differential equations (ODE's) with initial values and random perturbations. The idea is based on the fact that every shortest path possesses a simple geometric structure. This enables them to restrict the search in a set of feasible paths that share the same structure. The resulting search set is a union of sets of finite dimensional compact manifolds. Then, they use a gradient flow, based on an intermittent diffusion method, a global optimization strategy developed by the PI and collaborators in an earlier project, in conjunction with the level set framework, to obtain global shortest paths by solving a system of randomly perturbed initial value ODE's, whose dimension is dynamically changing. Compared to the existing methods, such as the combinatorial methods or PDE methods, the new algorithm is faster and easier to implement, and it can also handle cases in which obstacle shapes are arbitrary and/or the dimension of the base space is three or higher. This result was reported in a paper that is published by Applied and Computational Harmonic Analysis.

Following up on this project, the PI, Mr. Lu and Prof. Chow work together with Prof. Egerstede at ECE and his group to apply the optimal path planning to robotic control. In particular, they apply the path planning algorithms and developed a control strategy to design the best way to fly a unmanned vehicle in 3-D. The method is very efficient and robust. The results were submitted to a robotic conference in Tokyo, Japan. Another journal paper is in preparation and will be submitted in the future. Meanwhile, the PI and collaborators started to work on problems related to moving

obstacles, with which the problem becomes extremely hard, and there is no existing method for it so far.

- Random teleportation on graphs for global optimization and ranking:

Inspired by the famous metropolis-Hasting algorithm for global optimization, and based on their earlier work on Fokker-Planck equations on graphs, the PI and collaborators, including his postodoc, Dr. Xiaojing Ye, propose and analyze a potential induced random walk and its modification called random teleportation on finite graphs. The random teleportation can be used for multiple purposes, for example, for global optimizations, and for ranking problems on graphs. The teleportation is described by its transition probability, which is determined by the gaps between potential values of adjacent and teleportation nodes. We show that the steady state of this process has various useful properties. They present a continuous time analogue of the random walk and teleportation, and prove the lower bound on the order of exponential convergence rate to stationary distribution. The efficiency of proposed random walk and teleportation in search of global potential minimum on graphs are demonstrated by numerical tests. We discuss the condition of graphs and potential distributions for which the proposed approach can work inefficiently, and introduce the intermittent diffusion strategy to overcome the problem and improve the practical performance. This is a joint work with Prof. Chow and Dr. Ye. And the results are reported in a paper that is submitted.