Mitsubishi Electric Research Laboratories (MERL)

Annual Report

April 2013 through March 2014

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Welcome to Mitsubishi Electric Research Laboratories (MERL), the North American corporate R&D arm of Mitsubishi Electric Corporation. In this report, you will find descriptions of MERL and our projects.

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Mitsubishi Electric Research Laboratories

Mitsubishi Electric Research Laboratories (MERL) is the North American subsidiary of the corporate research and development organization of Mitsubishi Electric Corporation. MERL conducts application-motivated basic research and advanced development in optimization, control and signal processing.

MERL's mission—our assignment from Mitsubishi Electric:

- Generating new technology and intellectual property in areas of importance to Mitsubishi Electric.
- Significantly impacting Mitsubishi Electric's business: using our technical expertise in partnership with organizations in Mitsubishi Electric to produce new and improved products in Mitsubishi Electric's main areas of business.

MERL's vision—our goal for ourselves:

- Being one of the world's premiere research laboratories, doing long-term fundamental research that advances the frontiers of technology and makes lasting impacts on the world.
- Being the prime source of technology for Mitsubishi Electric in our areas of expertise.

MERL's values—how we operate:

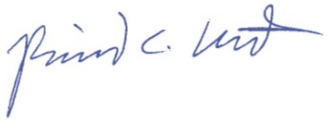
- Hiring very high quality researchers and supporting them strongly with a flexible work environment featuring teamwork both inside MERL and with our colleagues at Mitsubishi Electric.
- Participating in the world research community, publishing our work while maintaining the confidentiality of business information, and collaborating with interns and university researchers.

MERL focuses on five principal technology sectors:

Electronics & Communications - featuring wireless & optical signal processing technology.
Multimedia – featuring speech interfaces, video (de)coding & compressive sensing.
Data Analytics – featuring simulation, planning and optimization.
Spatial Analysis – featuring 3D imaging processing algorithms.
Mechatronics – featuring advanced control of electro-mechanical systems.

An Algorithms group supports all five sectors, developing fundamental algorithms.

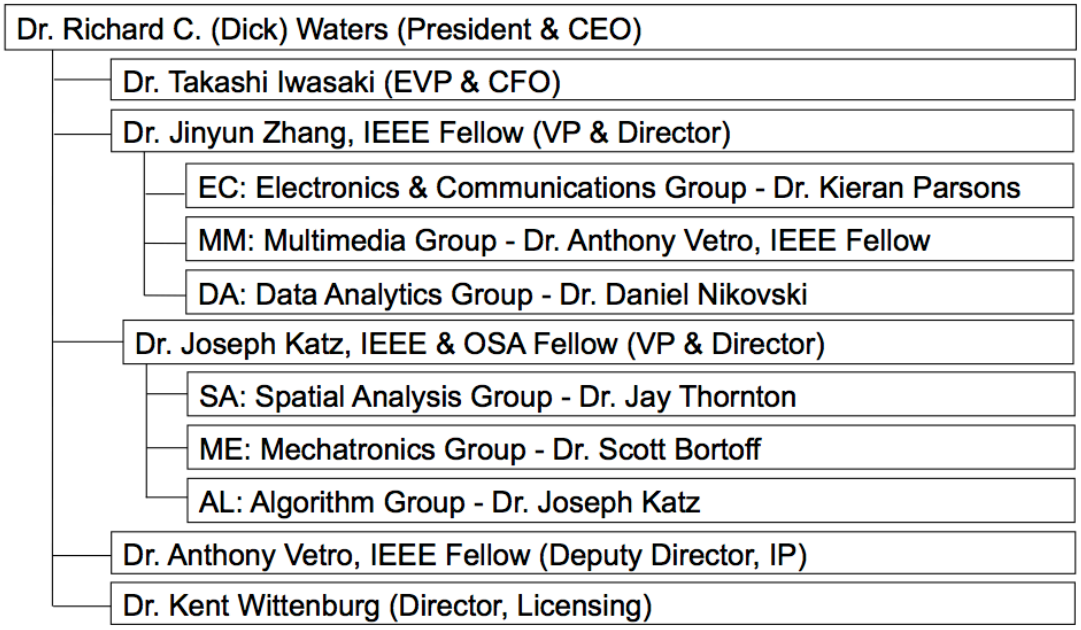
This annual report is a snapshot of MERL's web site. For additional and updated information please visit "www.merl.com".



Richard C. Waters
President, MERL

MERL Organization

MERL is organized as six groups centered on technology areas, which collaborate closely to achieve groundbreaking results. We use a relatively flat organization to enhance the opportunities for collaboration within MERL. The six members of the top management team work closely together, guiding all aspects of MERL's operation.



Richard C. (Dick) Waters *Ph.D., MIT, 1978*
President, CEO & MERL Fellow, ACM Distinguished Scientist

Dick Waters received his Ph.D. in artificial intelligence (AI). For the next 13 years he worked at the MIT AI Lab as a Research Scientist and co-principal investigator of the Programmer's Apprentice project. Dick was a founding member of MERL's Research Lab in 1991. As a MERL researcher, his work centered on multi-user interactive environments for work, learning, and play. In December 1999, he became CEO of MERL as a whole.

Takashi Iwasaki *Ph.D., Kyoto University, 1998*
Executive Vice President & CFO

Takashi Iwasaki joined Mitsubishi Electric's Industrial Electronics & Systems Laboratory in 1983 where he developed control technology for CNC, servo, robot, elevator, and other equipment. He moved to the Factory Automation Business Unit's Nagoya works in 2001. He transferred to the Advanced Technology R&D Center in 2006 where he rose to Senior Manager of the Mechanical Systems Department, before coming to MERL in 2012.

Joseph Katz *Ph.D., California Institute of Technology, 1981*
Vice President & Director, IEEE Fellow, OSA Fellow

After leading research in optical communications and optoelectronic devices & materials at Caltech's Jet Propulsion Laboratory for a number of years, Joseph Katz went to Symbol Technologies, where as Senior VP of R&D he participated in, initiated, and led projects in a wide range of technologies, including barcode/RFID data capture, optics, imaging, signal processing, computing, networking, security, biometrics, and communications. He joined MERL's management in 2004.

Jinyun Zhang *Ph.D., University of Ottawa, 1991*
Vice President, Director & MERL Fellow, IEEE Fellow

Before joining MERL in 2001, Jinyun worked for Nortel Networks for 10 years where she held engineering and management positions in the areas of VLSI design and advanced wireless & optical technology development. She joined MERL's management in 2001. In recognition of her contributions to broadband wireless transmission and networking technology she became an IEEE Fellow in 2008.

Anthony Vetro *Ph.D., Polytechnic University, 2001*
Deputy Director IP & Multimedia Group Manager, IEEE Fellow

Vetro joined MERL in 1996 and has been conducting research in the area of multimedia signal processing. He has contributed to the transfer and development of several technologies to digital television, surveillance, automotive, and satellite imaging systems. He has been an active participant in video coding standards and currently serves as Head of the US Delegation to MPEG. He joined MERL top management in 2014.

Kent Wittenburg *Ph.D., University of Texas at Austin, 1986*
Director Licensing

Kent manages MERL's licencing activities. He was formerly a lab Director at MERL for 9 years. Prior to joining MERL, he held positions at the Microelectronics and Computer Technology Corporation (MCC), Bellcore and Verizon/GTE Laboratories. His research interests include natural language processing, multimodal interfaces, visual languages, and information visualization. He is a Senior member of the ACM.

Mitsubishi Electric

One of the world's largest companies, Mitsubishi Electric Corporation has $41 billion in annual sales, $2.3 billion in operating profits (in the year ending in March 2014) and more than 120,000 employees around the world (see www.mitsubishielectric.com).

Mitsubishi Electric is composed of a wide range of operations. The primary business units are listed below.

Mitsubishi Electric Corp.

- **Information Systems & Network Services**
  IT Systems, Information Security/Encryption Systems, Business Solutions
- **Public Utility Systems**
  Government Systems, Transportation Systems, Very Large Display Devices
- **Energy & Industrial Systems**
  Electrical Generators, Power Transmission and Distribution Equipment
- **Building Systems**
  Elevators, Escalators, Building Monitoring/Security/Management Systems
- **Electronic Systems**
  Satellites, Radar Systems, Antennas, Electronic Toll Collection Systems
- **Communication Systems**
  Wired & Wireless Communication, Broadcasting Equipment and Systems
- **Living Environment & Digital Media Equipment**
  Televisions, Blu-ray Recorders, Air Conditioners, Solar Power Systems
- **Factory Automation Systems**
  Programmable Logic Controllers, Inverters, Servo-motors, Processing Machines
- **Automotive Equipment**
  Automotive Electrical Equipment, Car Electronics/Multimedia, Car Mechatronics
- **Semiconductor & Device**
  Optical Devices, High-Frequency & High-Power Semiconductors

Together, these ten business units produce most of Mitsubishi Electric's revenue. Due to the wide applicability of MERL's research, MERL works with them all.

It is worthy of note that there are over 30 major independent companies in the world that use the word "Mitsubishi" in their names. These companies include Mitsubishi UFJ Financial Group, Mitsubishi Corporation, Mitsubishi Heavy Industries, Mitsubishi Chemical Holdings and Mitsubishi Motors, all of which are also among the world's largest companies. They have shared roots in 19th century Japan; however, they have been separate for many years and Mitsubishi Electric has been separate from all of them since its founding in 1921.

Mitsubishi Electric's US Operations

A significant part of Mitsubishi Electric's sales are in North America and many of Mitsubishi Electric's business units have North American subsidiaries. The largest US operations are listed below (see www.mitsubishielectric-usa.com).

Mitsubishi Electric Automotive America, Inc. (Detroit MI & Mason OH)
Alternators, Ignition Coils, Automotive Electronics

Mitsubishi Electric Power Products, Inc. (Pittsburgh PA & Memphis TN)
Power Transmission Products, Rail Transportation Systems

Mitsubishi Electric USA, Inc. (Los Angeles CA & other cities)
Air Conditioners, Elevators, Photovoltaic Panels, High Power Semiconductors

Mitsubishi Electric Automation, Inc. (Chicago IL)
Factory Automation Equipment

Mitsubishi Electric Corporate R&D

Mitsubishi Electric has a global R&D network comprising five laboratories. The chart below summarizes the primary activities of these labs. MERL collaborates with all of these labs.

Corporate R&D Headquarters (Tokyo)

- **Advanced Technology R&D Center** (Amagasaki & Nagaokakyo, in greater Osaka)
  Power Electronics, Electro-mechanical, Ecology, Energy, Materials, Devices, Systems and Imaging Technologies
- **Information Technology R&D Center** (Ofuna, in greater Tokyo)
  Information, Communications, Multimedia, Electro-Optic and Microwave Technologies
- **Industrial Design Center** (Ofuna, in greater Tokyo)
  Product, Interface and Concept Design
- **Mitsubishi Electric Research Laboratories, Inc.** (Cambridge MA)
  Communications, Multimedia, Data Analytics, Imaging and Mechatronics Technologies
- **Mitsubishi Electric R&D Centre Europe, B.V.** (Rennes, France & Edinburgh, Scotland)
  Communications, Energy & Environmental Technologies
- **Mitsubishi Electric (China) Co, Ltd.** (Shanghai, China)
  Materials Science

Awards and Commendations

The high caliber of MERL's research and researchers is evident in a variety of ways. Two are highlighted below. The first is the members of our staff who are Fellows of technical societies. The second is best paper and other awards received from outside organizations. Listed below are awards for the period of this Annual Report.

Current Technical Society Fellows

Dr. Joseph Katz - Fellow, Institute of Electrical and Electronic Engineers
Dr. Joseph Katz - Fellow, Optical Society of America
Dr. Huifang Sun - Fellow, Institute of Electrical and Electronic Engineers
Dr. Anthony Vetro - Fellow, Institute of Electrical and Electronic Engineers
Dr. Jin Zhang - Fellow, Institute of Electrical and Electronic Engineers

Awards and Major Events

William T. Freeman & Michal Roth, "Orientation Histograms for Hand Gesture Recognition", IEEE International Workshop on Automatic Face and Gesture Recognition, Zurich, June, 1995 (FG 1995) was selected as the first "Test of Time" winner by the 10th IEEE conference on Automatic Face and Gesture Recognition, Shanghai, China June 2013 (FG 2013). The FG 2013 organizers decided to establish an award to recognize outstanding and influential papers that have appeared in past FG conferences. This paper was selected as the most important paper in the first three FG conferences (FG 1995, 1996 & 1998). Freeman & Roth both worked at MERL when this research was done. Currently, Freeman is a Professor & Associate Department Head of the Electrical Engineering and Computer Science Department at MIT.

Dehong Liu & Petros T. Boufounos, "Synthetic Aperture Imaging Using a Randomly Steered Spotlight", IEEE International Geoscience and Remote Sensing Symposium (IGARSS), July 2013, was selected as the winner of the IGARSS Symposium Prize Paper Award, presented for a paper judged to be of exceptional merit.

In September 2013, Jonathan LeRoux received the Awaya Prize Young Researcher Award (10 per year) from the Acoustical Society of Japan (ASJ).

It is also worthy of note that MERL had 8 papers accepted to the American Controls Conference (ACC) and 9 papers accepted to the IEEE International Conference on Acoustics, speech, and Signal Processing (ICASSP) — two of the most selective and prestigious Conferences related to MERL's areas of research. These results make MERL one of the most highly represented research labs in the world at these conferences with output greater than labs that are much larger.

Technical Staff

By providing a highly productive, collaborative environment, MERL believes that it is more than the sum of its parts; however, there is no question that its only important parts are its people. The following pages present the capabilities and interests of MERL's technical staff members as of the end of the period of this report. Additional information about their work can be found in the publications list and the project descriptions later in this report.

Luigi (Lou) Baccari *B.S., University of Massachusetts of Lowell*
Manager Computational & Network Services

Lou has 23 years of experience in the System and Network Administrations field. For the 6 years prior to joining MERL he worked at HP/Compaq's Cambridge Research Labs providing System and Network. Previous to that he worked for Force Computers, Lycos and Digital Equipment Corp. as Data Center Manger and in various System/Network Support roles.

John C. Barnwell III
Member Research Staff

John is a former Software Engineer developing configuration and database systems for the aircraft manufacturing, food processing, large truck manufacturing, and computer manufacturing industries. His interests include CNC control systems, and mechanical and electrical design. His current work involves the design and creation of the mechanical and electrical systems in support of experiments in all areas of MERL's research.

Mouhacine Benosman *Ph.D., Ecole Centrale de Nantes, 2002*
Principal Member Research Staff

Before coming to MERL in 2010, Mouhacine worked at universities in Rome, Italy, Reims, France and Glasgow, Scotland before spending 5 years as a Research Scientist with the Temasek Laboratories at the National University of Singapore. His research interests include modeling and control of flexible systems, non-linear robust and fault tolerant control, vibration suppression in industrial machines and multi-agent control with applications to smart-grid.

Scott A. Bortoff *Ph.D., University of Illinois Urbana-Champaign, 1992*
Mechatronics Group Manager

Scott's research interests are in applications of nonlinear and optimal control theory to motion control, path planning and process control problems. Before joining MERL in 2009, Scott led the Controls Group at the United Technology Research Center and previously was an Associate Professor at the University of Toronto.

Petros T. Boufounos *Sc.D., Massachusetts Institute of Technology, 2006*
Principal Member Research Staff

After completing his doctoral studies, Petros joined Rice University as a Postdoctoral associate until Jan. 2009, when he joined MERL. Since joining MERL, Petros has contributed in areas such as high-speed video acquisition, ultrasonic imaging, and privacy-preserving secure embeddings. His interests include signal acquisition and processing, signal representations and compressive sensing. He is also a visiting scholar at Rice University and an Associate Editor of IEEE Signal Processing Letters.

Matthew E. Brand *Ph.D., Northwestern University, 1994*
MERL Fellow

Brand develops and analyzes optimization algorithms for problems in logistics, control, perception, data-mining, and learning. Notable results include methods for parallel solution of quadratic programs, recomposing photos by re-arranging pixels, nonlinear dimensionality reduction, online singular value decomposition, 3D shape-from-video, and learning concise models of data.

Dirk Brinkman *J.D., Suffolk University Law School, 1990*
Senior Patent Counsel

Dirk's undergraduate and Masters work was in Medical Physics. Prior to joining MERL in 1998, he spent most of his career at Digital Equipment Corporation, first as an engineer and product manager in the Medical Systems Group and then as a Patent Attorney for Digital's Research Laboratories in Cambridge, MA and Palo Alto, CA.

Daniel J. Burns *Ph.D., Massachusetts Institute of Technology, 2010*
Principal Member Research Staff

At MIT, Dan developed mechanical designs and controllers for atomic force microscopes that image nano-scale features 1,000 times faster than commercially available instruments. Previously, Dan worked at the Commercial Aviation Systems division of Honeywell, and NASA's Goddard Space Flight Center. Currently, Dan works on control systems design and multi-physical modeling.

Robert A. Cohen *Ph.D., Rensselaer Polytechnic Institute, 2007*
Principal Member Research Staff

Prior to getting his Ph.D., Bob worked for 11 years at Philips Research Labs in NY on HDTV, scalable video streaming, video surveillance, and VLSI rapid prototyping. His current research interests are video coding & communications, and video, image & signal processing. He is an active participant in video coding standards.

Stefano Di Cairano *Ph.D., Carnegie Mellon University, 2004*
Principal Member Research Staff, Team Leader

Stefano's interests are model predictive control, constrained control, networked control systems, optimization algorithms, stochastic systems, and their applications to automotive, aerospace, logistics, and factory automation. Stefano is a member of the IEEE CSS Conference Editorial Board, and the Chair of the IEEE CSS Technical Committee on Automotive Controls.

Chunjie Duan *Ph.D., University of Colorado at Boulder, 2008*
Senior Principal Member Research Staff,

Prior to joining MERL, Chunjie worked for Alcatel, Qualcomm and Ericsson and other telecom companies for over 10 years. His research interests are in wireless and optical communications, digital signal processing and VLSI/CAD technology.

Tyler W. Garaas *Ph.D., University of Massachusetts Boston, 2009*
Principal Member Research Staff

Tyler's graduate work focused on neural simulation, human perception, high-performance computing, computer vision, and computer graphics. His current work focuses on software applications incorporating advanced algorithms in the areas of computational geometry, discrete and continuous optimization, and computer vision.

Guy Gold
Systems & Network Administrator

Guy Has 12 years of experience with Computing and Networking systems, with special interest in Unix/Linux systems. Previous to working at MERL, Guy worked as a Web Farm admin at Sutra Inc (Airline ticketing systems), as an IT consultant, as Network operations tech at Presbyterian Healthcare services (NM), and for Bezeq's (Israel) core Business IP/VPN support center.

Abraham M. Goldsmith *M.S., Worcester Polytechnic Institute, 2008*
Member Research Staff

At WPI, Abraham researched 3D ultrasound imaging, particularly the reconstruction of 3D volumes from sequences of 2D images. At MERL he has worked in areas ranging from wireless sensor networks to optical metrology and control. In addition to his research responsibilities, Abraham provides electrical and mechanical engineering support to the entire laboratory.

Piyush Grover *Ph.D., Virginia Polytechnic Institute & State Univ., 2010*
Member Research Staff

Piyush works at the intersection of dynamical systems, mechanics and control. He is interested in applying geometric and statistical methods for exploiting structure in nonlinear dynamical systems. Areas of applications include low-fuel space mission design, chaotic mixing, model reduction of distributed systems and nonlinear estimation.

Jianlin Guo *Ph.D., University of Windsor, 1995*
Senior Principal Member Research Staff

Jianlin worked at Waterloo Maple as a software developer before joining MERL in 1998. His primary research interests include reliable wireless networks, SmartGrid systems, vehicular communications, broadband wireless communications, and embedded systems.

Sohrab Haghighat, *Ph.D. University of Toronto, 2012*
Member Research Staff

Sohrab's research interests are in the areas of robust optimal control, model predictive control, multidisciplinary design optimization, flight dynamics and control, and nonlinear structural dynamics. His doctoral research was focused on control and design optimization of highly flexible aeroservoelastic wings. Sohrab was the recipient of the 2010 Etkin Medal for research excellence in the field of atmospheric flight mechanics.

Bret A. Harsham *B.S.,Massachusetts Institute of Technology*
Principal Member Research Staff

Before joining MERL in 2001, Bret worked at Dragon Systems on handheld and automotive speech products. At MERL, he works on research projects in the area of speech and multimodal applications, with a focus on effectiveness and usability. Past research projects have included work on multi-user touch interfaces and the safety & usability of in-car speech applications.

John R. Hershey *Ph.D., University of California San Diego, 2004*
Senior Principal Member Research Staff & Speech and Audio Team Leader

Before coming to MERL in 2010, Hershey was a researcher at IBM's Watson Research Center in New York, in the Speech Algorithms and Engines group, where he was team leader of the Noise Robustness project. He is now working on machine learning for signal enhancement and separation, speech recognition, language processing, and adaptive user interfaces.

Frederick J. Igo, Jr. *B.A., Le Moyne College, 1982*
Senior Principal Member Research Staff

Fred's professional interests are in software development and its process. He joined MERL in 1985 and has worked on various software technologies, including Distributed Computing, Distributed OLTP, Message Queuing, Mobile Agents, Data Mining, ZigBee, reliable wireless protocols and web development. Prior to joining MERL Fred worked at IPL systems.

Neera Jain *Ph.D., University of Illinois at Urbana-Champaign, 2013*
Visiting Member Research Staff

Neera's research interests lie at the intersection of control system design, dynamical modeling and analysis, and energy systems. Through her doctoral research, supported by the DOE Office of Science Graduate Fellowship, she developed a systematic methodology for deriving objective functions to be used in conjunction with optimal control algorithms for improving operational efficiency and performance of integrated energy systems.

Michael J. Jones Ph.D., Massachusetts Institute of Technology, 1997
Senior Principal Member Research Staff

Mike's main areas of interest are computer vision, machine learning and data mining. He has focused on algorithms for detecting and analyzing people in images and video including face detection and recognition and pedestrian detection. He is a co-inventor of the popular Viola-Jones face detection method. Mike has been awarded the Marr Prize at ICCV and the Longuet-Higgins Prize at CVPR.

Tamas Kalmar-Nagy *Ph.D. Cornell University, 2002*
Principal Member Research Staff

Tamas' research interests are in the theory and applications of nonlinear systems. Before joining MERL in 2012, Tamas worked at the United Technologies Research Center and then was an Assistant Professor at Texas A&M University. Tamas received a National Science Foundation CAREER award in 2009.

Kyeong Jin Kim *Ph.D., University of California Santa Barbara, 2000*
Senior Principal Member Research Staff

Kyeong Jin's research interests include transceiver design, performance analysis of spectrum sharing systems, design of cooperative communication systems. Since joining MERL, he has contributed in areas such as reliable communcations and E-WLAN system. Currently he is an Associate Editor of IEEE Communications Letters.

Andrew Knyazev *Ph.D., Inst of Numerical Math, Soviet Acad of Sci, 1985*
Distinguished Member Research Staff

During his 30 years in the academy, Andrew contributed to numerical analysis of partial differential equations and computational linear algebra, with emphasis on eigenvalue problems. His focus at MERL is on novel algorithms for image & video processing, data analytics, data transmission, and model predictive control.

Toshiaki Koike-Akino *Ph.D., Kyoto University, 2005*
Principal Member Research Staff

Prior to joining MERL in 2010, Toshiaki was a postdoctoral researcher at Harvard University. His research interests include signal processing, cooperative communications, coding theory, and information theory. He received best paper awards at IEEE GLOBECOM in 2008 and 2009.

Keisuke Kojima *Ph.D., University of Tokyo, 1990*
Senior Principal Member Research Staff

During his 8 years at the Central Research Laboratory, Mitsubishi Electric Corp. (Amagasaki, Japan), and 13 years AT&T/Lucent Bell Laboratories and other major US companies, Keisuke worked on R&D of semiconductor lasers and optical systems as a technical staff and later as a manager. At MERL he is currently working on simulations of optical devices and systems. He has more than 100 publications in journals and conference proceedings.

Dmytro Konobrytskyi *Ph.D., Clemson University, 2013*
Member Research Staff

Dmytro's research interests include high performance computing, highly parallel algorithms, 3D graphics, geometry processing, manufacturing simulation and automation. Before joining MERL, Dmytro worked at the Clemson University International Center for Automotive Research where he developed a fully automated GPU accelerated tool path planning and simulation system for 5-axis CNC milling machines.

Christopher Laughman *Ph.D., Massachusetts Institute Technology, 2008*
Principal Member Research Staff

Christopher's interests lie in the intersection of the modeling of physical systems and the experimental construction and testing of these systems, including simulation, numerical methods, and fault detection. He has worked on a variety of multi-physical systems, such as thermo-fluid systems and electromechanical energy conversion systems.

Jonathan Le Roux *Ph.D., University of Tokyo, 2009*
Principal Member Research Staff

Jonathan completed his B.Sc. and M.Sc. in Mathematics at the Ecole Normale Supérieure in Paris, France. Before joining MERL in 2011, he spent several years in Beijing and Tokyo. In Tokyo he worked as a postdoctoral researcher at NTT's Communication Science Laboratories. His research interests are in signal processing and machine learning applied to speech and audio.

Dehong Liu *Ph.D., Tsinghua University, 2002*
Principal Member Research Staff

Prior to joining MERL in 2010, Dehong worked at Duke University as a post-doctoral Research Associate (2003-2008), Research Scientist (2008-2010) and Sr. Research Scientist (2010). His main research interests include compressive sensing, signal processing and machine learning.

Ming-Yu Liu *Ph.D, University of Maryland College Park, 2012*
Member Research Staff

Before joining MERL in 2012, Ming-Yu was a graduate research assistant in the computer vision research laboratory in University of Maryland. His dissertation was about discrete optimizations methods for segmentation and matching. His research interests are in computer vision and machine learning.

Rui Ma *Ph.D., University of Kassel, 2009,*
Member Research Staff

Prior to joining MERL, Rui was a Senior Power Amplifier Research Engineer at Nokia Siemens Networks. His research interests include RF Power Device Modeling, Power Amplifier / Radio Front-End Architectures, non-linear microwave circuit design and high frequency measurement techniques.

Hassan Mansour, *Ph.D. University of British Columbia*, 2009
Member Research Staff

Hassan's research interests are in the areas of video compression, video transmission and compressed sensing. His PhD research developed resource allocation schemes for the transmission of scalable video content over bandwidth constrained wireless networks. His postdoctoral work developed adaptive sparse recovery algorithms for correlated signals from compressive measurements.

Tim K. Marks *Ph.D., University of California San Diego, 2006*
Principal Member Research Staff

Prior to joining MERL's Imaging Group in 2008, Tim did postdoctoral research in robotic Simultaneous Localization and Mapping in collaboration with NASA's Jet Propulsion Laboratory. His research at MERL spans a variety of areas in computer vision and machine learning, including face recognition under variations in pose and lighting, and robotic vision and touch-based registration for industrial automation.

David Millar *Ph.D., University College London (UCL), 2011*
Member Research Staff

Before joining MERL, David was a postdoctoral researcher at UCL, working on DSPs for coherent optical fiber transmission. Since then, he has been working on next generation systems and subsystems for the physical layer. He is particularly interested in advanced modulation formats, algorithms for equalization & carrier recovery, and reduced complexity transponders.

Daniel N. Nikovski *Ph.D., Carnegie Mellon University, 2002*
Data Analytics Group Manager

Dan's research is focused on algorithms for reasoning, planning, and learning with probabilistic models. His current work is on the application of such algorithms to hard transportation problems such as group elevator control and traffic prediction. He also has varied interests in the field of data mining.

Philip V. Orlik *Ph.D., State University of New York at Stony Brook, 1999*
Senior Principal Member Research Staff & Mobile Systems Team Leader

Prior to joining MERL in 2000, Phil worked as a simulation engineer for the MITRE Corporation. His current research interests include wireless communications and networking, signal processing for communication systems, queuing theory, and analytical modeling.

Kieran Parsons *Ph.D., University of Bristol, UK, 1996*
Electronics and Communications Group Manager

Kieran spent 12 years in Canada working at Nortel, BelAir Networks and AMCC on the system design of several wireless and optical technologies, including early work on electronic dispersion compensation for optical links. His research interests include optical communications network architecture and digital signal processing algorithms for coherent optical communications.

Ronald N. Perry *B.Sc., Bucknell University, 1981*
Distinguished Member Research Staff

Ron's fundamental research in computer graphics has resulted in numerous publications, a comprehensive patent portfolio, and the development of several meticulously crafted software and hardware products. Ron is best known for the Saffron Type System. The other highlight of his research is the development of 3D ADFs for CAD related products, including an NC simulation system demonstrating unprecedented precision and compactness.

Arvind Raghunathan *Ph.D., Carnegie Mellon University, 2004*
Principal Member Research Staff

Arvind's research focuses on algorithms for optimization of large-scale nonlinear and mixed integer nonlinear programs with applications in power grid, transportation systems and model-based control of processes. He previously worked at the United Technologies Research Center for 7 years developing optimization algorithms for aerospace, elevator, energy systems and security businesses.

Srikumar Ramalingam *Ph.D., INRIA Alpes, 2007*
Principal Member Research Staff

Srikumar's PhD thesis on generic imaging models received the INPG best thesis prize and the AFRIF thesis prize (honorable mention) from the French Association for Pattern Recognition. His research interests include multi-view geometry and discrete optimization. At MERL, he has been working on robotics and car-navigation projects.

Shantanu Rane *Ph.D., Stanford University, 2007*
Principal Member Research Staff

Shantanu's research interests are in the broad areas of signal processing and information theory. He is currently working on projects involving distributed source coding, secure biometrics, secure multiparty computation and visual inference.

Zafer Sahinoglu *Ph.D., New Jersey Institute of Technology, 2001*
Senior Principal Member Research Staff

Zafer's research interests include real time space-time adaptive processing, remote sensing, anomaly detection in power grid systems, battery modeling, robust optimization, and data mining. He participates in ANSI and NIST smart-grid standards activities. Also, he is currently pursuing an MBA at MIT Sloan School of Management.

Dohyung Seo PhD., *University of Florida, 2013*
Adjunct Member Research Staff

Dohyung's research interests include Partial Differential Equation-based image denoising/enhancement, image registration, larger motion interpolation and machine learning. His dissertation discussed deformable image registration on image surface manifolds and diffeomorphic large motion interpolation. At MERL, he works on deformable image registration.

Alan Sullivan *Ph.D., University of California at Berkeley, 1993*
Distinguished Member Research Staff, Dynamic Systems and Computational Geometry Team Leader

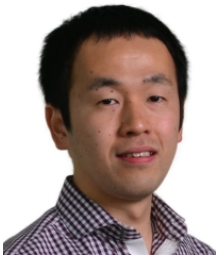
First at U.C. Berkeley, then at Lawrence Livermore National Laboratory, Alan studied interactions between ultra-high intensity femtosecond lasers and plasmas. Prior to joining MERL in 2007, he worked at a series of start-ups where he developed a novel volumetric 3D display technology. At MERL His research interests include computational geometry and computer graphics.

Hongbo Sun *Ph.D., Chongqing University, 1991*
Senior Principal Member Research Staff

Prior to Joining MERL in 2010, Hongbo was a principal applications Engineer at Oracle, and a technical architect at SPL WorldGroup. He is a registered Professional Engineer and has more than 20 years' experience in technical consulting, product development and research on electrical transmission and distribution system planning, analysis, operation, and automation.

Huifang Sun *Ph.D., University of Ottawa, 1986*
MERL Fellow / IEEE Fellow

After four years as a Professor at Fairleigh Dickinson University, Huifang moved to the Sarnoff Research Laboratory in 1990 becoming Technology Leader for Digital Video Communication. In 1995, Huifang joined MERL as the leader of MERL's video efforts. In recognition of his productive career in video processing, Huifang was made an IEEE Fellow in 2001.



Yuichi Taguchi *Ph.D. The University of Tokyo, 2009*
Principal Member Research Staff

Yuichi worked on light field compression and conversion techniques for 3D TV during his Ph.D. After joining MERL in 2009, he has worked on algorithms and sensors for industrial robotics and catadioptric imaging. His current research interests include computational photography and 3D reconstruction.

Koon Hoo Teo *Ph.D., University of Alberta 1990*
Senior Principal Member Research Staff, Power & Devices Team Leader

Koon Hoo was with Nortel for 15 years where he was actively involved in the research and implementation of 3G and 4G wireless systems. His work at MERL includes Cognitive Radio, Game Theory and Wireless Mesh for WiMAX and LTE systems. His current areas of research include Metamaterials, Power Amplifiers and Power Devices.

Jay E. Thornton *Ph.D., University of Michigan, 1982*
Spatial Analysis Group Manager

Prior to joining MERL in 2002, Jay worked at Polaroid Corporation for many years on human vision and image science problems concerning color reproduction, image quality, half toning, and image processing. At MERL he has become absorbed in research on vision for robotics, medical imaging, computational photography, computer human observation, dictionary learning, and processing of the 3D world.

Dong Tian *Ph.D., Beijing University of Technology, 2001*
Senior Principal Member Research Staff

Dong has been working in the field of image/video compression and processing for over 10 years. He was deeply involved in the standardization of H.264/MPEG-4 AVC, and then worked for its extension Multiview Video Coding. After joining MERL in 2010, he has continued research in 3D video coding/processing and has been an active participant in the 3DV group.

C. Oncel Tuzel *Ph.D., Rutgers University, 2008*
Principal Member Research Staff

Prior to his graduate studies, Oncel worked for 4 years on 3D game and simulation development. His doctoral work focused on statistical learning techniques on smooth manifolds and their applications to scene analysis. His research interests are in computer vision, machine learning, data mining, and computer graphics.

Jeroen van Baar *Ph.D., ETH Zurich, 2013*
Principal Member Research Staff

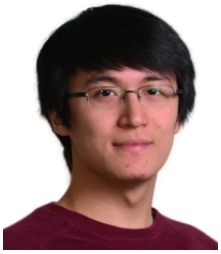
Jeroen came to MERL in 1997 as intern, and was subsequently hired as research associate. He temporarily left MERL to pursue a Ph.D. and returned early 2013. At MERL he has made contributions in the areas of computer graphics, computer vision and computational photography. His interests include 3D reconstruction, medical imaging, GP-GPU for computational photography and computer vision.

Gene V. Vinokur *J.D., Suffolk University Law School, 2011*
Patent Counsel

Gene graduated cum laude with distinction in Intellectual Property law. In addition, he holds advanced degrees in Mechanical Engineering and Computer Science. He is a member of Massachusetts Bar and has been a licensed patent practitioner since 2003.

Bingnan Wang *Ph.D., Iowa State University 2009*
Member Research Staff

Bingnan's doctoral work focused on the study of wave propagation in novel electromagnetic materials, including photonic crystals and meta-materials. His research interests include electromagnetics and photonics, and their applications to communications, imaging, and energy systems.



Ye Wang *Ph.D., Boston University, 2011*
Member Research Staff

Ye was a member of the Information Systems and Sciences Laboratory at Boston University, where he studied information-theoretically secure multiparty computation. His current research interests include information security, biometric authentication, and data privacy.

Yebin Wang *Ph.D., University of Alberta, 2008*
Principal Member Research Staff

Prior to joining MERL, Yebin worked on process control, software development and management, and nonlinear estimation theory for over ten years. At MERL, Yebin has been working on control and estimation for various automation and transportation systems. Yebin's research interests include nonlinear estimation/control theory and applications, optimal control, adaptive/learning systems, modeling and control of complex systems.

Shinji Watanabe *Ph.D., Waseda University, 2006*
Principal Member Research Staff

Prior to joining MERL in 2012, Shinji was a research scientist at NTT Communication Science Laboratories in Japan for 10 years, working on Bayesian learning for speech recognition, speaker adaptation, and language modeling. His research interests include speech recognition, spoken language processing, and machine learning.

Avishai Weiss *Ph.D., University of Michigan, 2013*
Member Research Staff

Avishai's doctoral research was on spacecraft orbital and attitude control. Prior to the University of Michigan, he studied at Stanford University, where he received a B.S. in Electrical Engineering and an M.S. in Aeronautics and Astronautics. Avishai's interests are in constrained control, model predictive control, and time-varying systems.

William S. Yerazunis *Ph.D., Rensselaer Polytechnic Institute, 1987*
Senior Principal Member Research Staff, Hardware Team Leader

Bill has worked in numerous fields, including parallel computation, SETI, jet engine production, real-time signal processing, expert systems, pattern recognition, text classification, wireless power, and meta-materials. He is the author of the CRM114 spam filter, has appeared as a continuing character in educational science television, and was voted one of the 50 most important people in computer network security by Network World magazine.

Peizhen Zhu *Ph.D., University of Colorado Denver, 2012*
Visiting Member Research Staff

Peizhen's research interests are matrix computation, such as numerical linear algebra and optimization, data mining, and numerical analysis. Her focus at MERL is on novel algorithms for model predictive control and data analytics.

Publications

The following lists the major publications by members of the MERL staff during the period of this report. A publication is considered major if it appeared in a refereed journal, a refereed conference proceeding or some other significant publication such as a book.

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Research

The body and soul of any research lab is its portfolio of research projects. Therefore it is appropriate that the main body of this annual report consists of descriptions of research projects being done at MERL. The reports are grouped into six topic areas corresponding to MERL's six research groups.

Electronics & Communications - wireless and optical communications, advanced signal processing, optical and semiconductor devices, and electro-magnetics, with application to product areas such as terrestrial and trans-oceanic optical networks, train and automotive connectivity and electronics, power equipment and systems for smart grid, RF power amplifiers & front-end modules, and wireless charging.

Multimedia – Acquisition, representation, processing and security of multimedia, as well as enhanced interaction with multimedia. Core technical strengths are in various aspects of signal processing ranging from video and speech processing, to information forensics and security, as well as signal processing theory and sensing methods.

Data Analytics – Innovative high-performance algorithms that can be applied to electrical power systems, various transportation systems (trains, elevators, car navigation), heating, ventilation, and air conditioning (HVAC) systems and solutions, and factory automation. The application of these algorithms minimizes costs, increases reliability, improves energy efficiency, and reduces environmental impact of products.

Spatial Analysis - Processing data from across space and time to extract meaning and build representations of objects and events in the world. Detection, classification, and recognition based on machine learning and physical modeling; 3D reconstruction, location, and inference; computational imaging for optimized information capture; Dictionary Learning for signal processing; tracking; and multi-modal sensor integration.

Mechatronics - If it moves, we control it. Advanced control algorithms, nonlinear dynamical systems, system modeling & dynamic analysis, mechatronics design, innovative system concepts, and 3D adaptively-sampled distance fields applications.

Algorithms - Solution methods for optimization problems involving very large numbers of variables in the areas of information theory & coding; stochastic network utility maximization; sensing, perception, inference, and learning.

Electronics & Communications

The Electronics & Communications Group conducts fundamental and applied research in the areas of wireless and optical communications, advanced signal processing, optical and semiconductor devices, and electro-magnetics. Our research has application to product areas such as terrestrial and trans-oceanic optical networks, train and automotive connectivity and electronics, power equipment and systems for smart grid, RF power amplifiers and front-end modules, and wireless charging.

Wireless research focuses on the development of novel physical and network layer algorithms, combined with advanced channel modeling, to enable high reliability wireless networks for machine-to-machine networking, high mobility systems and vehicular networks. Our signal processing work involves detection, localization and applied optimization algorithms for applications such as Smart Grid.

Optical work focuses on signal processing algorithms and error control coding for coherent long haul and sub-sea fiber-optic communications, and the development of novel photonic integrated circuits to support optical communications applications.

Power & RF work emphasizes highly efficient wideband power amplifier technology and semiconductor devices, as well as electro-magnetic analysis and manipulation, for applications such as wireless power transfer to static and mobile devices.

Recent Research

An LLC-Based Planar Wireless Power Transfer System for Multiple Devices

Citation: Liu, N.; Wang, B., "An LLC-Based Planar Wireless Power Transfer System for Multiple Devices", *IEEE Applied Power Electronics Conference and Exposition (APEC)*, DOI: 10.1109/APEC.2014.6803798, pp. 3411-3417, March 2014
Contacts: Bingnan Wang

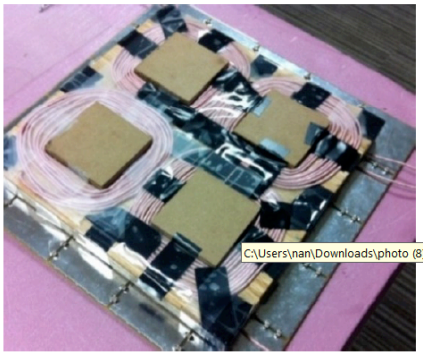


Fig. 9. The hardware system with four parallel-connected transmitting coils.

Wireless power transfer (WPT) technology has become a popular idea in battery charging for both low- and high-power applications, such as mobile-phones and electric vehicles (EV). For charging portable devices, common ideas apply location sensing and turn on specific coils under the loads. This paper proposes a universal WPT system for multiple electronics devices. The system is based on an LLC circuit, with an additional inductor added on the primary LC circuit, making the system less sensitive to load variations while maintaining a reasonable voltage-range. Parallel-connected transmitting coils provide independent charging for each load. A simple yet effective variable-frequency control algorithm is used to provide maximum and balanced charging power to the loads. Simulation results have demonstrated the advantages of the system – optimal operating frequency in a small range, simple control and independent charging for each load.

Experimental Demonstration of 24-Dimensional Extended Golay Coded Modulation with LDPC

Citation: Millar, D.S.; Koike-Akino, T.; Maher, R.; Lavery, D.; Paskov, M.; Kojima, K.; Parsons, K.J.; Thomsen, B.; Savory, S.J.; Bayvel, P., "Experimental Demonstration of 24-Dimensional Extended Golay Coded Modulation with LDPC", *Optical Fiber Communication Conference and Exposition (OFC),* DOI: 10.1364/OFC.2014.M3A.5, ISBN: 978-1-55752-993-0, March 2014
Contacts: David Millar, Toshiaki Koike-Akino, Keisuke Kojima, Kieran Parsons

We experimentally demonstrate ultra-long haul transmission of 24-D extended Golay coded modulation with LDPC. Compared with LDPC coded DP-BPSK, an increase of 15% in reach was shown, with a 3 dB increase in launch power margin at a transmission distance of more than 16,000 km.

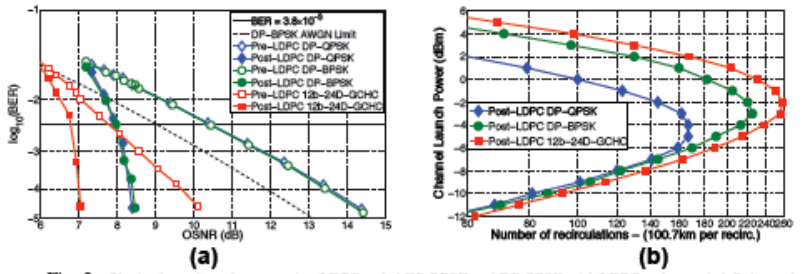


Fig. 2. Single channel results comparing LDPC coded DP-BPSK and DP-QPSK with LDPC and extended Golay coded QPSK at a net bit rate of 46.6 Gb/s (including FEC overhead). Back-to-back results are presented in (a), while maximum reach assuming an outer HD-FEC BER threshold of 3.8×10^{-3} is presented in (b).

Cycle Slip-Mitigating Turbo Demodulation in LDPC-Coded Coherent Optical Communications

Citation: Koike-Akino, T. Kojima, K.; Millara, D.S.; Parsons, K.J.; Miyata, Y.; Massumoto, W.; Sughiara, T.; Mizuochi, T., "Cycle Slip-Mitigating Turbo Demodulation in LDPC-Coded Coherent Optical Communications", *Optical Fiber Communication Conference and Exposition (OFC),* DOI: 10.1364/OFC.2014.M3A.3, ISBN: 978-1-55752-993-0, March 2014

Contacts: Toshiaki Koike-Akino, Keisuke Kojima, David Millar, Kieran Parsons

We show that an iterative demodulation with soft-decision feedback information from an FEC decoder can efficiently mitigate cycle slips. With 3% pilot insertion, the turbo QPSK demodulation achieves 1.05dB gain even in the presence of frequent cycle slips.

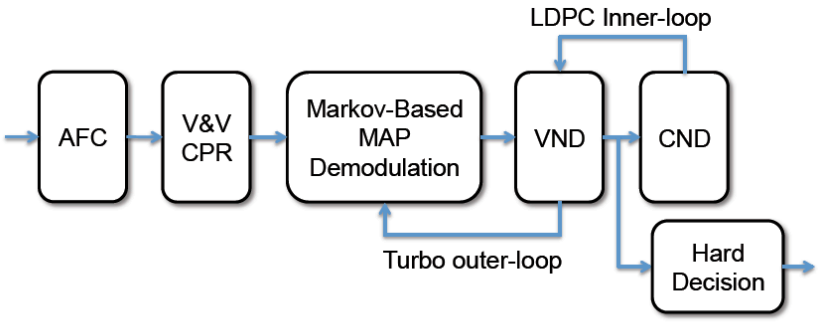


Fig. 1: Turbo demodulation for cycle-slip recovery.

Ripple Design of LT Codes for BIAWGN Channels

Citation: Sorensen, J.H.; Koike-Akino, T.; Orlik, P.V.; Ostergaard, J.; Popovski, P., "Ripple Design of LT Codes for BIAWGN Channels", *IEEE Transactions on Communications*, DOI: 10.1109/TCOMM.2013.122013.130116, ISSN: 0090-6778, Vol. 62, Issue 2, pp. 434-441, February 2014

Contacts: Toshiaki Koike-Akino, Philip Orlik

This paper presents a novel framework, which enables a design of rateless codes for binary input additive white Gaussian noise (BIAWGN) channels, using the ripple-based approach known for binary erasure channels (BEC). We reveal that several aspects of the analytical results from the BEC also hold in BIAWGN channels. The presented framework is applied in a code design example, which shows promising results compared to existing work. In particular it shows a great robustness towards variations in the signal-to-noise power ratio (SNR), contrary to existing codes.

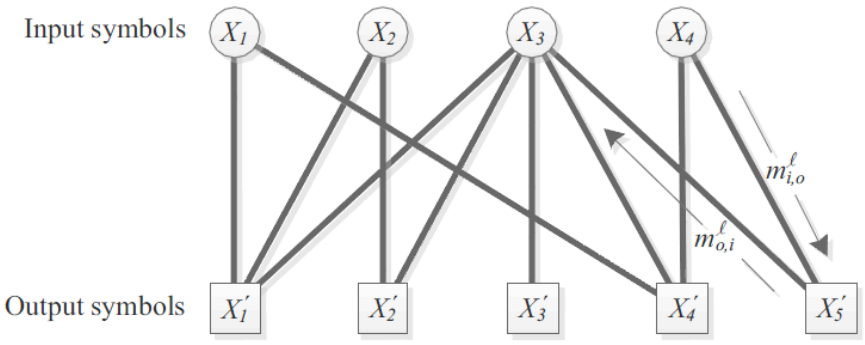


Fig. 1. Graphical representation of an LT code.

A 24-Dimensional Modulation Format Achieving 6 dB Saymptotic Power Efficiency

Citation: Millar, D.S.; Koike-Akino, T.; Kojima, K.; Parsons, K.J., "A 24-Dimensional Modulation Format Achieving 6 dB Asymptotic Power Efficiency", *Signal Processing in Photonic Communications*, dx.doi.org/10.1364/SPPCOM. 2013. SPM3D.6, ISBN: 978-1-55752-981-7, July 2013

Contacts: David Millar, Toshiaki Koike-Akino, Keisuke Kojima, Kieran Parsons

We propose modulation using the extended Golay code over the 24D hypercube, achieving 6 dB asymptotic power efficiency with 1 b/s/Hz/pol spectral efficiency. Noise tolerance is improved by 3 dB over DP-BPSK at a BER of 10^{-3}.

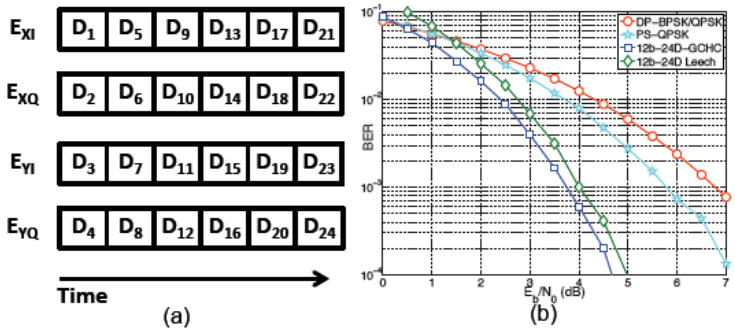


Fig. 1. (a) Example mapping of 24D basis to 4D carrier using time domain. (b) Noise sensitivity of 12b-24D-GCHC compared with DP-BPSK/QPSK, PS-QPSK and the 12b-24D Leech lattice.

Nonlinear Adaptive Estimation of the State of Charge for Lithium-ion Batteries

Citation: Wang, Y.; Fang, H.; Sahinoglu, Z.; Wada, T.; Haa, S., "Nonlinear Adaptive Estimation of the State of Charge for Lithium-ion Batteries", *IEEE Conference on Decision and Control (CDC)*, DOI: 10.1109/CDC.2013.6760567, ISSN: 0743-1548, pp. 4405-4410, December 2013

Contacts: Yebin Wang, Zafer Sahinoglu

This paper considers State of Charge (SoC) estimation of Lithium-ion battery. Different from various prior art, where estimation is performed based on local linearization of a nonlinear battery model, a nonlinear adaptive observer is proposed to estimate the SoC and the parameters of a simplified but nonlinear battery model. A major advantage of the proposed approach is the possibility to establish the exponential stability of the resultant error dynamics of state and parameter estimation. Simulation validates the effectiveness of the proposed approach.

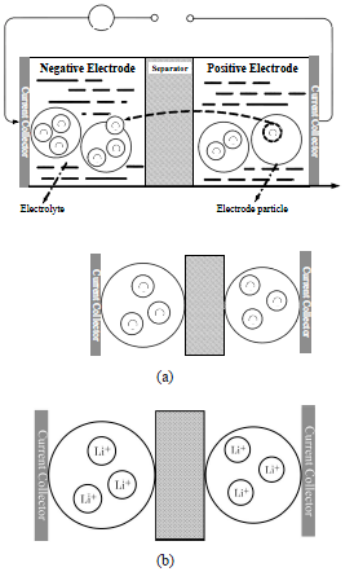


Fig. 1. Schematic characterization of battery dynamics: (a) the battery charging process; (b) the single-particle model.

A Low-loss Integrated Beam Combiner Based on Polarization Multiplexing

Citation: Wang, B.; Kojima, K.; Koike-Akino, T.; Parsons, K.J.; Nishikawa, S.; Yagyu, E., "A Low-loss Integrated Beam Combiner Based on Polarization Multiplexing", *OSA Technical Digest*, dx.doi.org/10.1364/IPRSN.2013.JT3A.17, ISBN: 978-1-55752-981-7, July 2013

Contacts: Bingnan Wang, Keisuke Kojima, Toshiaki Koike-Akino, Kiernan Parsons

We present a design of an integrated beam combiner which cascades power combiners and polarization converter/combiner. The proposed device has 2 dB lower loss than power combiners and is more fabrication-tolerant than wavelength combiners.

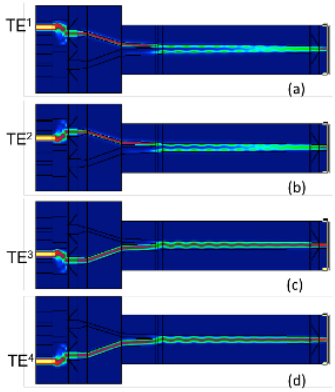


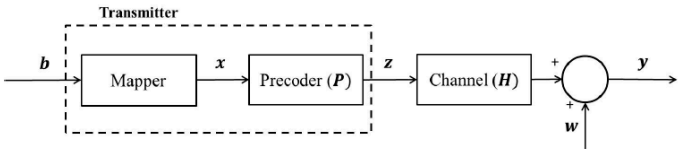
Fig. 4. Simulated field distribution in the 4 × 1 optical combiner for four input wavelengths (a) 1295.56 nm (b) 300.05 nm, (c) 1304.58 nm, and (d) 1309.14 nm.

On Probabilistic Data Association for Achieving Near-Exponential Diversity over Fading Channels

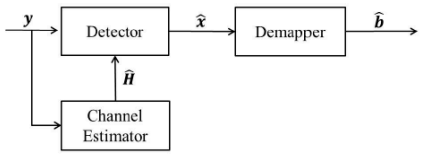
Citation: Yellepeddi, A.; Kim, K.J.; Duan, C.; Orlik, P.V., "On Probabilistic Data Association for Achieving Near-Exponential Diversity over Fading Channels", *IEEE International Conference on Communications (ICC)*, DOI: 10.2209/icc.2013.6655449, ISSN: 1550-3607, pp. 5409-5414, June 2013

Contacts: Kyeong Jin Kim, Philip Orlik

Machine-to-Machine (M2M) wireless communication requires the transmission of short blocks of data with high reliability over fading channels. We discuss the use of the probabilistic data association (PDA) detector in conjunction with precoding to design high-performance systems for these links. First, the performance of the traditional PDA algorithm with precoding over ideal Rayleigh fading links is analyzed, which provides insight into its performance, and evidence of an error floor at high SNRs. Then, a novel ordering mechanism is proposed that takes advantage of the precoder characteristics. It is shown by simulation that the proposed modified algorithm can achieve near-ML performance for block sizes as small as 32 symbols.



(a) Transmitter and Channel



(b) Receiver

Fig. 1: Block diagram of the considered system.

Wireless Power Transfer: Metamaterials and Array of Coupled Resonators

Citation: Wang, B.; Yerazunis, W.S.; Teo, K.H., "Wireless Power Transfer: Metamaterials and Array of Coupled Resonators", *Proceedings of the IEEE*, DOI: 10.1109/JPROC.2013.2245611, ISSN: 0018-9219, Vol. 101, Issue 6, pp. 1359-1368, June 2013

Contacts: Bingnan Wang, William Yerazunis, Koon Hoo Teo

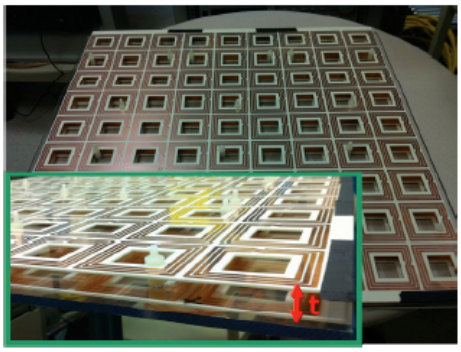


Fig. 2. A picture of the planar metamaterial. Inset shows the details, with t the spacing between two planes.

We report some recent progress on wireless power transfer (WPT) based on resonant coupling. Two major technologies are discussed: the use of metamaterials, and arrays of coupled resonators. With a slab of metamaterial, the near-field coupling between two resonant coils can be enhanced; the power transfer efficiency between coils is boosted by the metamaterial. The design of metamaterial slabs for near-field wireless power transfer is shown; recent experimental results on wireless power transfer efficiency improvement with metamaterial are also presented. By using an array of resonators, the range of efficient power transfer can be greatly extended and wireless power can be provided to both static and mobile devices. Analytical and numerical models are used to evaluate the performance of a WPT system with an array of resonators; recent experimental developments are also presented.

Fast Frequency and Phase Estimation in Three Phase Power Systems

Citation: Chen, Z.; Sahinoglu, Z.; Li, H., "Fast Frequency and Phase Estimation in Three Phase Power Systems", *IEEE Power & Energy Society General Meeting(PES)*, DOI: 10.1109/PESMG.2013.6672077, ISSN: 1944-9925, pp. 1-5, July 2013

Contacts: Zafer Sahinoglu

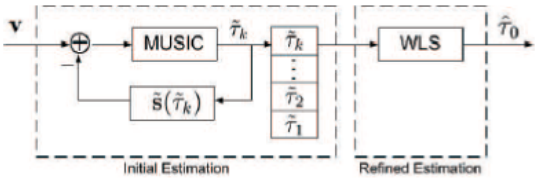


Fig. 2. Structure of the proposed IWLS parameter estimation algorithm

In this paper, we investigate the fundamental frequency and phase estimation problem in a balanced three-phase power system with harmonic distortion. An estimation algorithm that can rapidly track the fast-changing frequency and phase by using quarter cycle samples is proposed. Specifically, the data model in the three-phase power system is first converted to the noise-corrupted single-phase harmonic signal model by using the Clarke transformation. A new weighted least squares (WLS) parameter estimator, which refines the initial estimates from the standard estimation techniques, is computed by utilizing the harmonic structure of the signal. Since the initial estimates become unreliable with limited samples, we propose an iterative algorithm to polish the initial estimates for WLS. Numerical results show that the proposed estimator outperforms conventional estimators, especially in a data-limited case.

A 40-dBm High Voltage Broadband GaN Class-J Power Amplifier for PoE Micro-Basestations

Citation: Ma, R.; Goswami, S.; Yamanaka, K.; Komatsuzaki, Y.; Ohta, A., "A 40-dBm High Voltage Broadband GaN Class-J Power Amplifier for PoE Micro-Basestations", *IEEE MTT-S International Microwave Symposium Digest (IMS)*, DOI: 10.1109/MWSYM.2013.6697607, ISSN: 0149-645X, pp. 1-3, June 2013

Contacts: Rui Ma

A broadband, efficient and linear RF power amplifier for 4G multi-standard micro-base-stations is presented. With an optimized Class-J matching network and a new commercially available high voltage 10W GaN HEMT, output power around 40.5dBm is measured across 1.65-2.70GHz with 55-72% drain efficiency at 1-dB compression point under CW stimulus. To the author's best knowledge, this is the first Class-J prototype operating at 47V, enabling power over Ethernet applications without any external voltage regulation, thereby further reducing the bill of materials and improving the overall system efficiency.

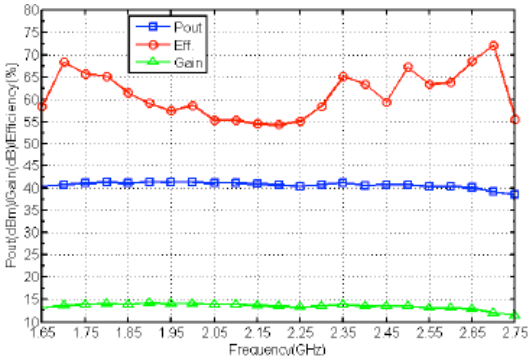


Fig. 6. Measured output power, drain efficiency, and gain under CW frequency swept from 1.65GHz-2.75GHz at P_{in} of 27.2dBm.

Load Balanced Routing for Low Power and Lossy Networks

Citation: Liu, X.; Guo, J.; Bhatti, G.; Orlik, P.V.; Parsons, K.J., "Load Balanced Routing for Low Power and Lossy Networks", *IEEE Wireless Communications and Networking Conference (WCNC)*, DOI: 10.1109/WCNC.2013.6554908, ISSN: 1525-3511, ISBN: 978-1-4673-5938-2, pp. 2238-2243, April 2013

Contacts: Jianlin Guo, Philip Orlik, Kieran Parsons

Using the RPL routing protocol some sensor nodes may have much heavier workload in terms of packets forwarded than others due to the uneven deployment of sensor nodes in large areas, and heterogeneous traffic patterns in the network. Such unbalanced workload distribution will result in some sensor nodes quickly exhausting their energy, therefore shorten the overall network lifetime. We propose a load balanced routing protocol based on RPL, named LB-RPL, to achieve balanced workload distribution in the network. Targeted at the low-power and lossy network environments, LB-RPL detects workload imbalance in a distributed and non-intrusive fashion.

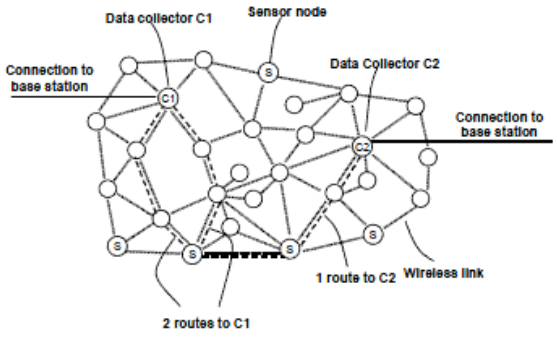


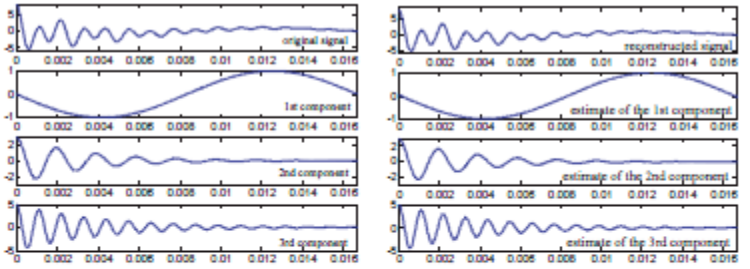
Fig. 1. An example deployment of a two-tier large-scale sensor networks for environment monitoring.

Transient Disturbance Detection for Power Systems with a General Likelihood Ratio Test

Citation: Song, X.; Sahinoglu, Z.; Guo, J., "Transient Disturbance Detection for Power Systems with a General Likelihood Ratio Test", *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, DOI: 10.1109/ICASSP.2013.6638175, ISSN: 1520-6149, pp. 2839-2843, May 2013

Contacts: Zafer Sahinoglu, Jianlin Guo

A voltage/current transient typically caused by islanding and switching operations is treated as an adverse phenomenon that degrades power quality, and it may cause damage to electrical equipment. In this paper, the transient detection problem is formulated as a binary hypothesis test: normal signal (null) vs. transient (alternative). The sampled data is described by a sinusoid under the null hypothesis, while a sum of damped sinusoids is utilized to model the alternative one. As no prior knowledge is imposed on complex amplitudes, frequencies, or damping factors in signal modeling, the general likelihood ratio test (GLRT) is employed to fulfill the task. Probability of detection of 0.98 is achieved at a SNR of 27dB and probability of false alarm of 0.0005.



(a) The original signal and its three components (b) The reconstructed signal and its three estimated components

Wireless Power Transfer with Magnetic Conductor Reflectors

Citation: Wu, J.; Wang, B.; Yerazunis, W.S.; Teo, K.H., "Wireless Power Transfer with Artificial Magnetic Conductors", *IEEE Wireless Power Transfer (WPT)*, DOI: 10.1109/WPT.2013.6556906, ISBN: 978-14673-5008-2, pp. 155-158, May 2013

Contacts: Bingnan Wang, William Yerazunis, Koon Hoo Teo

In this paper, a wireless power transfer system (WPT) with magnetically coupled resonators is studied. The idea is to use a reflector to enhance the coupling coefficient and the transfer efficiency is proposed and analyzed. A perfect magnetic conductor (PMC) was used in numerical calculations in order to study the performance of a reflector. In the WPT system we studied, efficiency is increased from 48% without reflector to 72% with PMC reflector. With recently developed metamaterial technologies, artificial PMCs can be designed and fabricated for such reflectors.

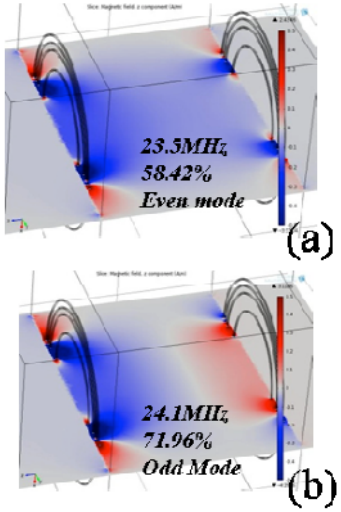


Fig. 8. Magnetic field distribution of the WPT system with PMC as reflectors for (a) even mode and (b) odd mode. Frequency and corresponding power transfer efficiency are given in insets.

Multimedia

Multimedia research at MERL is centered on the acquisition, representation, processing and security of multimedia, as well as enhanced interaction with multimedia. Core technical strengths are in various aspects of signal processing ranging from video and speech processing to information forensics and security as well as theory and sensing methods. Our research results are applied to a wide range of products including automotive electronics and audio-visual equipment; surveillance and access control systems; space/airborne systems for remote sensing; and information technology systems. We are also actively engaged in the international standardization of next-generation video compression schemes as well as biometric security and related metrics.

Digital video research focuses on 3D video coding, perceptual video coding, distributed source coding, and visual inference. We are also engaged in the development of next-generation video compression standards.

Speech and audio research emphasizes speech and multimodal interfaces including voice search, statistical dialog systems and speech enhancement. We are also exploring acoustic modeling, robust acoustic acquisition, and structured learning for speech and audio processing.

Information security work seeks to create technology for privacy-preserving signal processing including secure computation of encrypted signals, as well as computation of statistics from anonymized data.

Research on compressive sensing technology and applications includes signal acquisition and design, signal modeling and reconstruction algorithms, and array signal processing techniques.

Recent Research

Discriminative Methods for Noise Robust Speech Recognition: A CHiME Challenge Benchmark

Citation: Tachioka, Y.; Watanabe, S.; Le Roux, J.J.H.; Hershey, J.R., "Discriminative Methods for Noise Robust Speech Recognition: A CHiME Challenge Benchmark", *International Workshop on Machine Listening in Multisource Environments (CHiME)*, June 2013

Contacts: Shinji Watanabe, Jonathan Le Roux, John Hershey

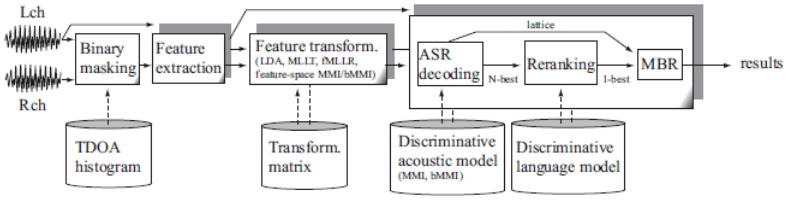


Fig. 1. Schematic diagram of the proposed system.

The recently introduced second CHiME challenge is a difficult two-microphone speech recognition task with non-stationary interference. Here we pursue a novel approach, focusing on state-of-the-art ASR techniques such as discriminative training and various feature transformations, in addition to simple noise suppression methods based on prior-based binary masking with estimated angle of arrival. In addition, we propose an augmented discriminative feature transformation that can introduce arbitrary features to a discriminative feature transform, an efficient combination method of Discriminative Language Modeling (DLM) and Minimum Bayes Risk (MBR) decoding in an ASR post-processing stage, and preliminarily investigate the effectiveness of deep neural networks for reverberated and noisy speech recognition.

Non-negative Dynamical System with Application to Speech and Audio

Citation: Fevotte, C.; Le Roux, J.J.H.; Hershey, J.R., "Non-negative Dynamical System with Application to Speech and Audio", *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, DOI: 10.1109/ icassp.2013. 6638240, ISSN: 1520-6149, pp. 3158-3162, May 2013

Contacts: Jonathan Le Roux, John Hershey

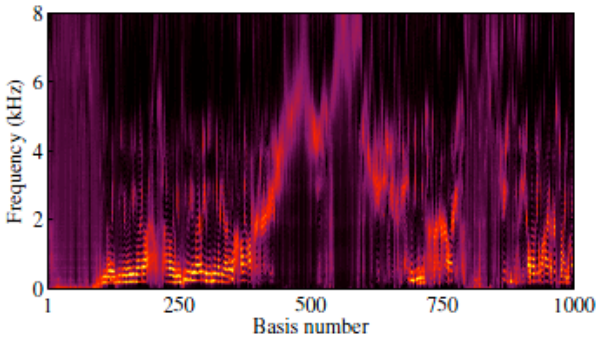


Fig. 1. Example of learned W on female speech (frame length: 512), sorted greedily by similarity.

Non-negative data arise in a variety of important signal processing domains, such as power spectra of signals, pixels in images, and count data. This paper introduces a novel non-negative dynamical system (NDS) for sequences of such data, and describes its application to modeling speech and audio power spectra. The NDS model can be interpreted both as an adaptation of linear dynamical systems (LDS) to non-negative data, and as an extension of non-negative matrix factorization (NMF) to support Markovian dynamics. Results show that the model can capture the dynamics of speech in a useful way.

Ensemble Learning for Speech Enhancement

Citation: Le Roux, J.J.H.; Watanabe, S.; Hershey, J.R., "Ensemble Learning for Speech Enhancement", *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, DOI: 10.1109/WASPAA.2013.6701888, ISSN: 1931-1168, pp. 1-4, October 2013

Contacts: Jonathan Le Roux, Shinji Watanabe, John Hershey

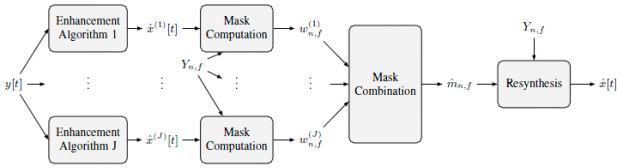


Figure 1: Overview of the framework.

Over the years, countless algorithms have been proposed to solve the problem of speech enhancement from a noisy mixture. Many have succeeded in improving at least parts of the signal, while often deteriorating others. Based on the assumption that different algorithms are likely to enjoy different qualities and suffer from different flaws, we investigate the possibility of combining the strengths of multiple speech enhancement algorithms, formulating the problem in an ensemble-learning framework. As a first example of such a system, we consider the prediction of a time-frequency mask obtained from the clean speech, based on the outputs of various algorithms applied on the noisy mixture. We consider several approaches involving various notions of context and various machine learning algorithms for classification, in the case of binary masks, and regression, in the case of continuous masks. We show that combining several algorithms in this way can lead to an improvement in enhancement performance, while simple averaging or voting techniques fail to do so.

Statistical Dialogue Management using Intention Dependency Graph

Citation: Yoshino, K.; Watanabe, S.; Le Roux, J.J.H.; Hershey, J.R., "Statistical Dialogue Management using Intention Dependency Graph", *International Joint Conference on Natural Language Processing (IJCNLP)*, pp. 962-966, October 2013

Contacts: Shinji Watanabe, Jonathan Le Roux, John Hershey

We present a method of statistical dialogue management using a directed intention dependency graph (IDG) in a partially observable Markov decision process (POMDP) framework. The transition probabilities in this model involve information derived from a hierarchical graph of intentions. In this way, we combine the deterministic graph structure of a conventional rule-based system with a statistical dialogue framework. The IDG also provides a reasonable constraint on a user simulation model, which is used when learning a policy function in POMDP and dialogue evaluation. Thus, this method converts a conventional dialogue manager to a statistical dialogue manager that utilizes task domain knowledge without annotated dialogue data.

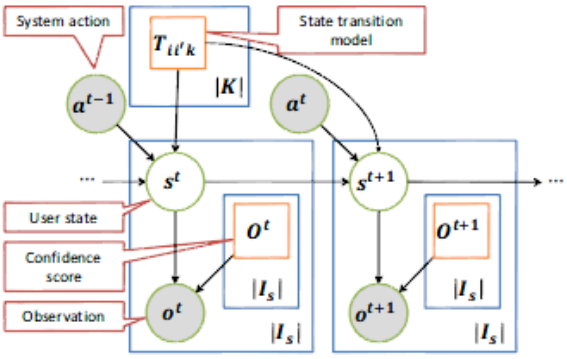


Figure 2: Graphical model of user state sequences given system actions a^{t-1} and a^t. This graphical model shows user behavior that is observed from the system.

Source Localization in Reverberant Environments using Sparse Optimization

Citation: Le Roux, J.J.H.; Boufounos, P.T.; Kang, K.; Hershey, J.R., "Source Localization in Reverberant Environments using Sparse Optimization", *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, DOI: 10.1109/ICASSP.2013.6638473, ISSN: 1520-6149, pp. 4310-4314, May 2013

Contacts: Jonathan Le Roux, Petros Boufounos, John Hershey

We demonstrate that recently-developed sparse recovery algorithms can be used to improve source localization in reverberant environments. By formulating the localization problem in the frequency domain, we are able to efficiently incorporate information that exploits the reverberation instead of considering it a nuisance to be eliminated. In this formulation, localization becomes a joint-sparsity support recovery problem, which can be solved using model-based methods. We also develop a location model, which further improves performance. Using our approach, we are able to recover more sources than the number of sensors. In contrast to conventional wisdom, we demonstrate that reverberation is beneficial in source localization, as long as it is known and properly accounted for.

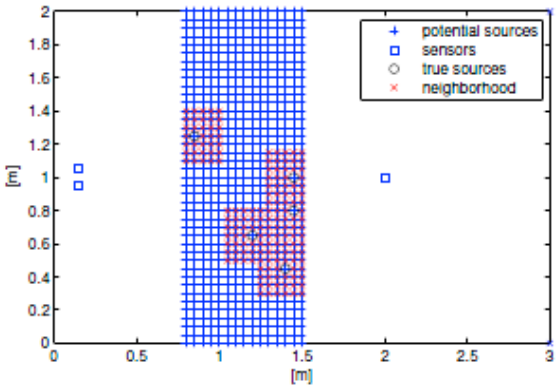


Fig. 1. Room setup.

Standardized Extensions of High Efficiency Video Coding (HEVC)

Citation: Sullivan, G.J.; Boyce, J.M.; Chen, Y.; Ohm, J-R.; Segall, C.A.; Vetro, A., "Standardized Extensions of High Efficiency Video Coding (HEVC)", *IEEE Journal of Selected Topics in Signal Processing*, DOI: 10.1109/JSTSP.2013.2283657, ISSN: 1932-4553, Vol. 7, Issue 6, pp. 1001-1016, December 2013

Contacts: Anthony Vetro

This paper describes extensions to the High Efficiency Video Coding (HEVC) standard that are active areas of current development in the relevant international standardization committees. While the first version of HEVC is sufficient to cover a wide range of applications, needs for enhancing the standard in several ways have been identified, including work on range extensions for color format and bit depth enhancement, embedded-bitstream scalability, and 3D video. The standardization of extensions in each of these areas will be completed in 2014, and further work is also planned. The design for these extensions represents the latest state of the art for video coding and its applications.

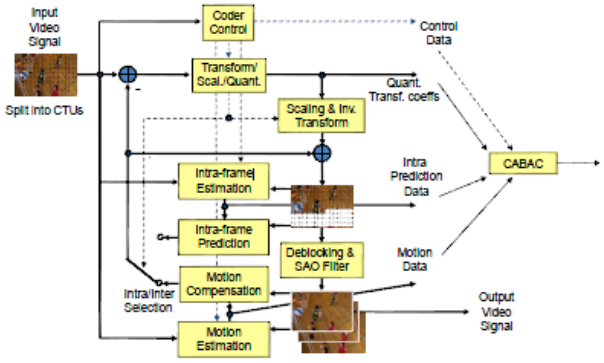


Fig. 1. Hybrid video encoder for HEVC.

Temporal Perceptual Coding Using a Visual Acuity Model

Citation: Adzic, V.; Cohen, R.A.; Vetro, A., "Temporal Perceptual Coding Using a Visual Acuity Model", *IS&T / SPIE Electronic Imaging Science and Technology*, Human Vision and Electronic Imaging XIX, DOI: 10.1117/12.2043130, Vol. 9014, February 2014

Contacts: Robert Cohen, Anthony Vetro

This paper describes research and results in which a visual acuity (VA) model of the human visual system (HVS) is used to reduce the bitrate of coded video sequences, by eliminating the need to signal transform coefficients when their corresponding frequencies will not be detected by the HVS. The VA model is integrated into the state of the art HEVC HM codec. Compared to the unmodified codec, up to 45% bitrate savings are achieved while maintaining the same subjective quality of the video sequences. Encoding times are reduced as well.

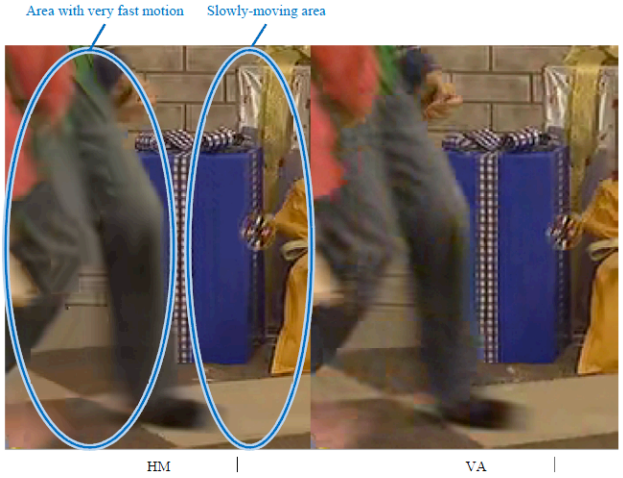


Figure 6.Magnified region of a decoded *ParkScene* frame containing significant differences in motion. Both the HM and VA frames were coded using QP=30.

Depth Based 3D Video Formats and Coding Technology

Citation: Vetro, A.; Muller, K., "Depth Based 3D Video Formats and Coding Technology", *Emerging Technologies for 3D Video: Creation, Coding, Transmission and Rendering*, DOI: 10.1002/9781118583593.CH8, ISBN: 978-1-1183-5511-4, Part 2: Section 8, April 2013

Contacts: Anthony Vetro

There are many types of 3D display systems including classic stereoscopic systems that require special-purpose glasses to more sophisticated multiview auto-stereoscopic displays that do not require glasses (Konrad and Halle, 2007). While stereoscopic systems only require two views, the multiview displays have much higher data throughput requirements since 3D is achieved by essentially emitting multiple videos in order to form view-dependent pictures. Such displays can be implemented, for example, using conventional high-resolution displays and parallax barriers; other technologies include lenticular overlay sheets and holographic screens. Each view dependent video sample can be thought of as emitting a small number of light rays in a set of discrete viewing directions – typically between eight and a few dozen for an auto-stereoscopic display.

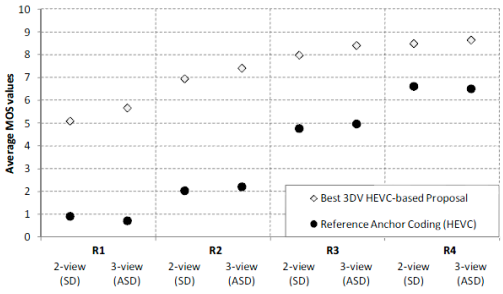
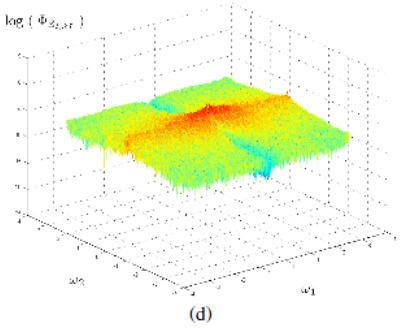


Fig. 8.15: 3D-HEVC-based subjective results: Averaged MOS scores over all eight test sequences at four different bit rates R1-R4 according to Table 8.2: Evaluation of 2-view scenario on stereoscopic display (SD), evaluation of 3-view scenario on auto-stereoscopic 28-view display (ASD).

An Analytical Model for Synthesis Distortion Estimation in 3D Video

Citation: Fang, L.; Cheung, N.-M.; Tian, D.; Vetro, A.; Sun, H.; Au, O.C., "An Analytical Model for Synthesis Distortion Estimation in 3D Video", *IEEE Transactions on Image Processing*, DOI: 10.1109/TIP.2013.2287608, ISSN: 1057-7149, Vol. 23, Issue 1, pp. 185-189, January 2014

Contacts: Dong Tian, Anthony Vetro, Huifang Sun

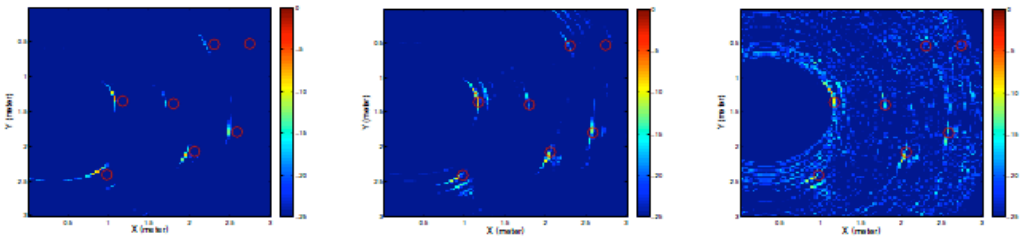


We propose an analytical model to estimate the synthesized view quality in 3D video. The model relates errors in the depth images to the synthesis quality, taking into account texture image characteristics, texture image quality and the rendering process. Specifically, we decompose the synthesis distortion into texture-error induced distortion and depth-error induced distortion. We analyze the depth-error induced distortion using an approach combining frequency and spatial domain techniques. Experiment results with video sequences and coding/rendering tools used in MPEG 3DV activities show that our analytical model can accurately estimate the synthesis noise power.

Blind Multi-path Elimination by Sparse Inversion in Through-the-Wall-Imaging

Citation: Mansour, H.; Liu, D., "Blind Multi-path Elimination by Sparse Inversion in Through-the-Wall-Imaging", *IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP)*, DOI: 10.1109/CAMSAP.2013.6714056, ISBN: 978-1-4673-3144-9, pp. 256-259, December 2013

Contacts: Hassan Mansour, Dehong Liu

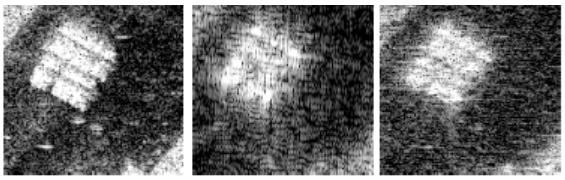


We propose a multi-path elimination by sparse inversion (MESI) algorithm that removes the clutter induced by internal wall reflections in a Through-the-Wall-Imaging (TWI) system without prior knowledge of the scene geometry. Our approach iteratively recovers the time-domain primary impulse responses of targets behind the front wall then finds a delay convolution operator that best maps the primary impulse response of each target to the multi-path reflections available in the received signal. We present numerical simulations that demonstrate the effectiveness of MESI in locating targets inside a room with unknown dimensions or wall parameters and highlight the robustness of our scheme to severe measurement noise.

Synthetic Aperture Imaging Using a Randomly Steered Spotlight

Citation: Liu, D.; Boufounos, P.T., "Synthetic Aperture Imaging Using a Randomly Steered Spotlight", *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, DOI: 10.1109/IGARSS.2013.6721810, ISSN: 2153-6996, pp. 919-922, July 2013

Contacts: Dehong Liu, Petros Boufounos



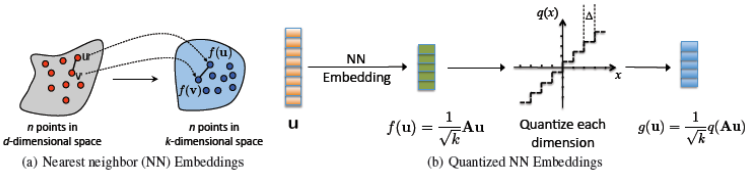
We develop a new approach to synthetic aperture imaging inspired by recently developed compressive sensing (CS) methods. Our approach modifies the beam steering pattern of conventional sliding spotlight-mode systems and randomizes it such that with each pulse of the beam illuminates a different, randomly chosen, part of the imaged area. The randomization allows the acquisition of the area of interest with a significantly larger effective aperture compared to the conventional sliding spotlight mode and, therefore, with significantly larger resolution. Our experimental results demonstrate that the proposed randomly steered spotlight array can improve imaging resolution, as measured by the reconstruction SNR and the phase error, without compromising the covered area size.

Quantized Embeddings: An Efficient and Universal Nearest Neighbor Method for Cloud-based Image Retrieval

Citation: Rane, S.D.; Boufounos, P.T.; Vetro, A., "Quantized Embeddings: An Efficient and Universal Nearest Neighbor Method for Cloud-based Image Retrieval", *SPIE Conference on Applications of Digital Image Processing XXXVI*, DOI: 10.1117/12.2022286,Vol. 8856, September 2013

Contacts: Petros Boufounos, Anthony Vetro

We propose a rate-efficient, feature-agnostic approach for encoding image features for cloud-based nearest neighbor search. We extract quantized random projections of the image features under consideration, transmit these to the cloud server, and perform matching in the space of the quantized projections. The advantage of this approach is that, once the underlying feature extraction algorithm is chosen for maximum discriminability and retrieval performance (e.g., SIFT, or eigen-features), the random projections guarantee a rate-efficient representation and fast server-based matching with negligible loss in accuracy. We report experimental results of image retrieval on two image databases with different feature spaces; one using SIFT features and one using face features extracted using a variant of the Viola-Jones face recognition algorithm. For both feature spaces, quantized embeddings enable accurate image retrieval combined with improved bit-rate efficiency and speed of matching, when compared with the underlying feature spaces.



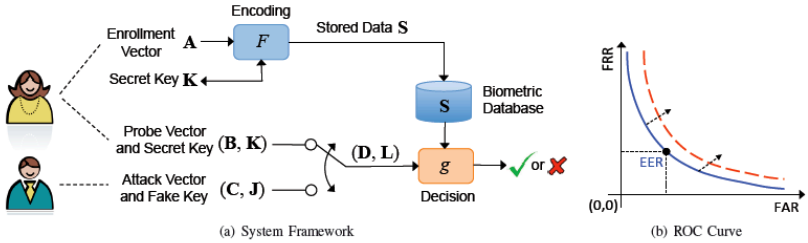
(a) Nearest neighbor (NN) Embeddings (b) Quantized NN Embeddings

Figure 1. (a) The Johnson-Lindenstrauss Lemma guarantees the existence of a NN embedding that preserves pairwise Euclidean distances. (b) A quantized NN embedding is derived by first obtaining a Johnson-Lindenstrauss embedding by multiplying the vectors in the canonical feature space by a random matrix, followed by scalar quantization of each element in the vector of randomized measurements.

Secure Biometrics: Concepts, Authentication Architectures & Challenges

Citation: Rane, S.D.; Wang, Y.; Draper, S.C.; Ishwar, P., "Secure Biometrics: Concepts, Authentication Architectures and Challenges", *IEEE Signal Processing Magazine*, DOI: 10.1109/MSP.2013.2261691, ISSN: 1053-5888, Vol. 30, Issue 5, pp. 51-64, September 2013

Contacts: Ye Wang



(a) System Framework (b) ROC Curve

Biometrics are an important and widely used class of methods for identity verification and access control. Biometrics are attractive because they are inherent properties of an individual. They need not be remembered like passwords, and are not easily lost or forged like identifying documents. At the same time, biometrics are fundamentally noisy and irreplaceable. The proliferation of biometric usage raises critical privacy and security concerns that, due to the noisy nature of biometrics, cannot be addressed using standard cryptographic methods. In this article we present an overview of "secure biometrics", also referred to as "biometric template protection", an emerging class of methods that address these concerns.

On the Benefits of Sampling in Privacy Preserving Statistical Analysis on Distributed Databases

Citation: Lin, B-R; Wang, Y.; Rane, S.D., "On the Benefits of Sampling in Privacy Preserving Statistical Analysis on Distributed Databases", *arXiv:1304.4613*, Computer Science, Cryptography and Security, April 2013

Contacts: Ye Wang

We consider a problem where mutually untrusting curators possess portions of a vertically partitioned database containing information about a set of individuals. The goal is to enable an authorized party to obtain aggregate (statistical) information from the database while protecting the privacy of the individuals, which we formalize using Differential Privacy. This process can be facilitated by an untrusted server that provides storage and processing services but should not learn anything about the database. This work describes a data release mechanism that employs Post Randomization (PRAM), encryption and random sampling to maintain privacy, while allowing the authorized party to conduct an accurate statistical analysis of the data. Encryption ensures that the storage server obtains no information about the database, while PRAM and sampling ensures individual privacy is maintained against the authorized party.

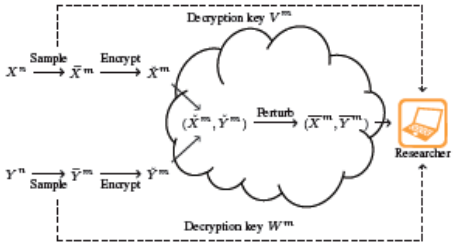


Fig. 3. Curators Alice and Bob independently encrypt their databases with a one time pad and provide it to a cloud server. The server samples m respondents and then performs PRAM to guarantee privacy of the individual database respondents. A researcher can derive joint statistics or joint type based on the sanitized data, without compromising the privacy of the respondents. Neither the statistics nor the individual data entries are revealed to the cloud server.

Data Analytics

Data Analytics technologies aim to improve the performance of devices, systems, and business processes by means of collecting data, constructing predictive models from that data, and making improved decisions based on the constructed models. The Data Analytics group at MERL has been working on both predictive and decision analytics, as well as supporting fields such as signal processing, numerical methods, and information systems infrastructure. The focus of the group is on innovative high-performance algorithms that can be applied to various product lines of Mitsubishi Electric, including electrical power systems, various transportation systems (trains, elevators, cars), heating, ventilation, and air conditioning (HVAC) systems and solutions, and factory automation. The application of these algorithms minimizes costs, maximizes profits, increases reliability, improves energy efficiency, and reduces environmental impact of products.

Research on predictive analytics, supported by advances in the fields of statistical machine learning and data management aims to create accurate data-driven models of electromechanical and thermo dynamical systems, as well as models of complex natural and man-made phenomena such as road traffic and demand for electrical power. The rapidly increasing amount of available sensor data, popularly known as Big Data, necessitates the development of very scalable learning algorithms with computational complexity that is close to linear in the number of data records and measured variables.

Decision optimization research emphasizes numerical methods for fast solution of continuous and discrete optimization problems, and finds application in the analysis of electrical power systems and Smart Grids that include renewable power sources with intermittent output as well as highly variable loads such as electrical vehicles. Many problems in transportation systems such as train operation optimization, group elevator scheduling, and route guidance for car navigation, can be reduced to planning and optimization problems. Energy consumption in buildings can be minimized by solving sequential decision and optimization problems, both at the level of individual air conditioning devices, as well as at the level of entire buildings.

Recent Research

Markov Decision Processes for Train Run Curve Optimization

Citation: Nikovski, D.N.; Lidicky, V.; Zhang, W.; Kataoka, K.; Yoshimoto, K., "Markov Decision Processes for Train, Run Curve Optimization", *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS)*, ISSN: 2165-9400, pp. 1-6, October, 2012

Contacts: Daniel N. Nikovski

We propose three computationally efficient methods for finding optimal run curves of electrical trains, all based on the idea of approximating the continuous dynamics of a moving train by a Markov Decision Process (MDP) model. Deterministic continuous train dynamics are converted to stochastic transitions on a discrete model by observing the similarity between the properties of convex combinations and those of probability mass functions. The resulting MDP uses barycentric coordinates to effectively represent the cost-to-go of the approximated optimal control problem.

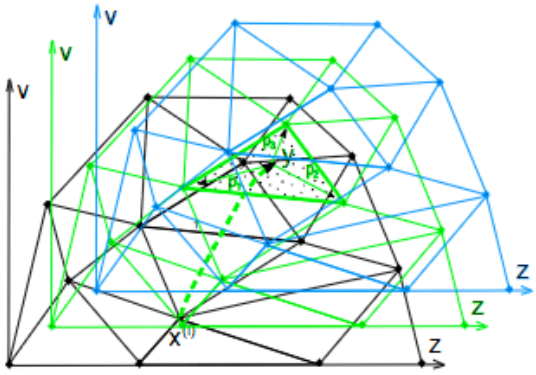


Figure V.1. The MDP for the fixed-end-time version of the problem has a separate replica of the triangulation for multiple time steps, organized into time slices. Three slices are shown here, in black, green, and blue, respectively. Each transition is from one time slice to the next (here, a transition is shown from $x^{(i)}$ in the black slice to y in the green slice).

Fast Refrigerant Property Calculations Using Interpolation-Based Methods

Citation: Laughman, C.R.; Zhao, Y.; Nikovski, D.N, "Fast Refrigerant Property Calculations Using Interpolation-Based Methods", *International Refrigeration and Air Conditioning Conference at Purdue*, July 2012

Contacts: Christoper R. Laughman, Daniel N. Nikovski

An interpolation-based method for computing refrigerant properties which can be used in simulations of vapor-compression air-conditioning equipment is presented. This method uses bicubic functions to interpolate between samples of the Helmholtz energy surface as a function of temperature and density. Three beneficial characteristics of this method are discussed: speed, accuracy, and consistency, as well as a means for using a variety of different independent variables are also presented. The implementation of this method is discussed, and experimental results for property calculations for refrigerant R-134a are presented which compare favorably to standard Newton-based equation of state methods.

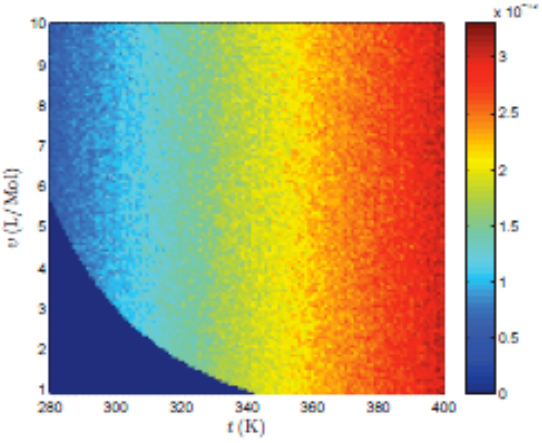


Figure 2: Computation consistency error: E_t.

Two-Level State Estimation Method for Power Systems with SCADA and PMU Measurements

Citation: Sun, H.; Wang, Z.; Nikovski, D.N., "Two-Level State Estimation Method for Power Systems with SCADA and PMU Measurements", *IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, DOI: 10.1109/ISGT-Asia.2012.6303127, pp. 1-5, May 2012
Contacts: Hongbo Sun, Daniel N. Nikovski

This paper proposes a two-level hybrid state estimation method for power systems with SCADA and PMU measurements. A power system is decoupled into PMU observed areas and SCADA observed areas based on its system measurement configuration and topology connectivity, and the states of areas are solved by a two-level computational procedure. The first level uses PMU measurements and pseudo measurements derived from SCADA measurements to formulate a linear state estimation model for each PMU observed area, from which the states of the buses in the area are estimated. The second level uses the SCADA measurements and pseudo measurements generated by results at the first level to formulate a nonlinear state estimation model for each SCADA observed area. The weighted least squares method is used to solve the models at the two levels.

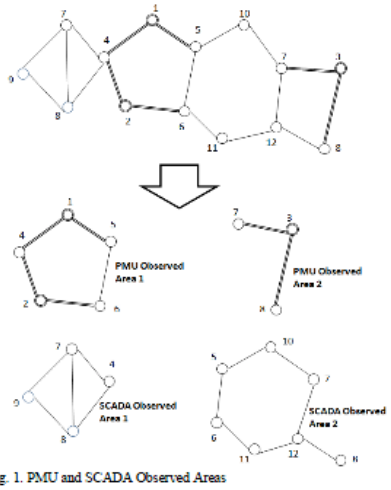


Fig. 1. PMU and SCADA Observed Areas

Matcher Composition Methods for Automatic Schema Matching

Citation: Nikovski, D.N.; Esenther, A.; Ye, X.; Shiba, M.; Takayama, S., "Matcher Composition Methods for Automatic Schema Matching", *Enterprise Information Systems*, Lecture Notes in Business Information Processing, DOI: 10.1007/978-3-643-4065406_7, ISSN: 1865-1348, Vol. 141, pp. 108-123, December 2013
Contacts: Daniel Nikovski

We address the problem of automating the process of deciding whether two data schema elements match (that is, refer to the same actual object or concept), and propose several methods for combining evidence computed by multiple basic matchers. One class of methods uses Bayesian networks to account for the conditional dependency between the similarity values produced by individual matchers that use the same or similar information, so as to avoid overconfidence in match probability estimates and improve the accuracy of matching. Experimental results suggest that the matching accuracy of the Bayesian composite matchers can significantly exceed that of the individual component matchers, and the careful selection of optimization switches can improve matching accuracy even further.

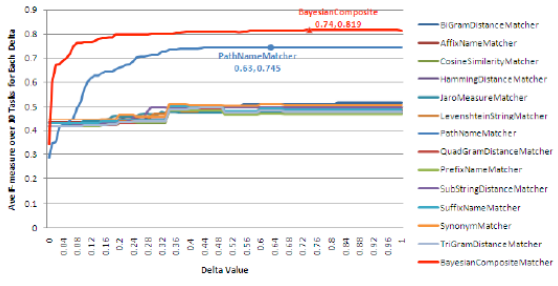


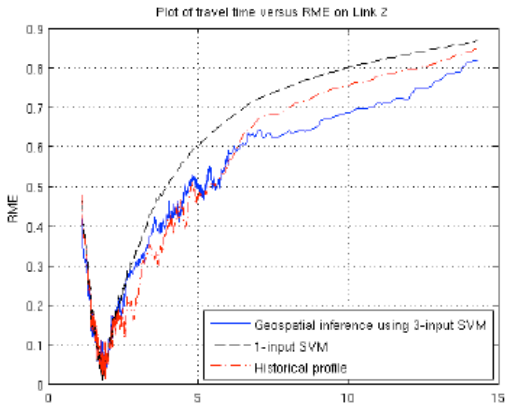
Fig. 4. Comparison of average f-measure between the Bayesian Composite Matcher and all other matchers.

Predicting Link Travel Times from Floating Car Data

Citation: Jones, M.J.; Geng, Y.; Nikovski, D.N.; Hirata, T., "Predicting Link Travel Times from Floating Car Data", *International IEEE Conference on Intelligent Transport Systems (ITSC)*, DOI: 10.1109/ITSC.2013.6728483, pp. 1756-1763, October 2013

Contacts: Michael Jones, Daniel Nikovski

We study the problem of predicting travel times for links (road segments) using floating car data. We examine the problem of predicting link travel times when no recent probe car data is available for estimating current travel times. This is a serious problem that arises when using probe car data for prediction. Our solution, which we call geospatial inference, uses floating car data from nearby links to predict travel times on the desired link. Geospatial inference leads to improved travel time estimates for congested links compared to standard methods.



Estimating Locations of Single-phase-to-ground Faults of Ungrounded Distribution Systems

Citation: Sun, H.; Nikovski, D.N.; Takano, T.; Kojima, Y.; Ohno, T., "Estimating Locations of Single-phase-to-ground Faults of Ungrounded Distribution Systems", *IEEE/PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, DOI: 10.1109/ISGTEurope.2013.6695314, pp. 1-5, October 2013

Contacts: Hongbo Sun, Daniel Nikovski

We determine single-phase-to-ground fault locations of ungrounded distribution systems based on measurements collected from the feeder breakers and intelligent switches during the fault. The method first narrows down the possible faulted area into a specific feeder section based on the reactive power factors of residual powers determined for the breakers and switches. Then the power consumption of each individual load in the faulted section is determined based on measurements at the boundaries of the section, and load profiles for each individual load.

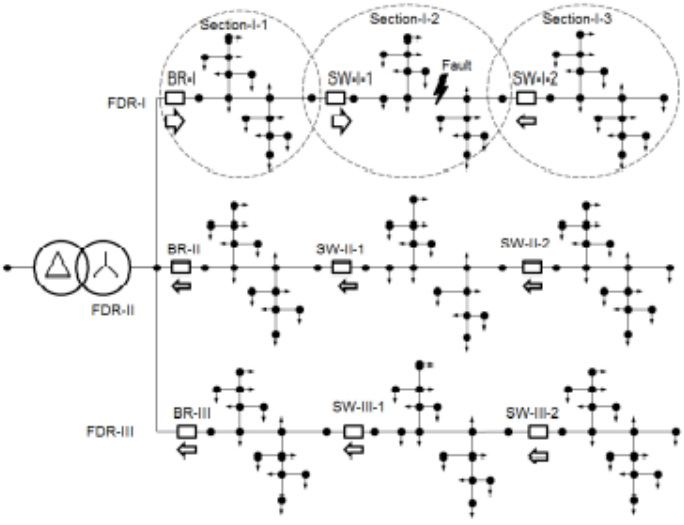


Fig.1. An example of ungrounded distribution system

Line Fault Analysis of Ungrounded Distribution Systems

Citation: Sun, H.; Nikovski, D.N.; Takano, T.; Kojima, Y.; Ohno, T., "Line Fault Analysis of Ungrounded Distribution Systems", *North American Power Symposium (NAPS)*, DOI: 10.1109/NAPS.2013.6666851, pp. 1-6, September 2013

Contacts: Hongbo Sun, Daniel Nikovski

The fault condition of a line fault is integrated into the nodal admittance matrix of the faulted line to be modeled. The distribution system is partitioned into a main network and a set of lateral networks to be solved. The main network is formed by the connected paths between the terminal buses of the faulted line, and generation sources, and solved by a Gauss-Seidel method. A lateral network is formed by one of the buses of main network and all buses and branches downstream to the bus, and solved by a backward and forward sweep method.

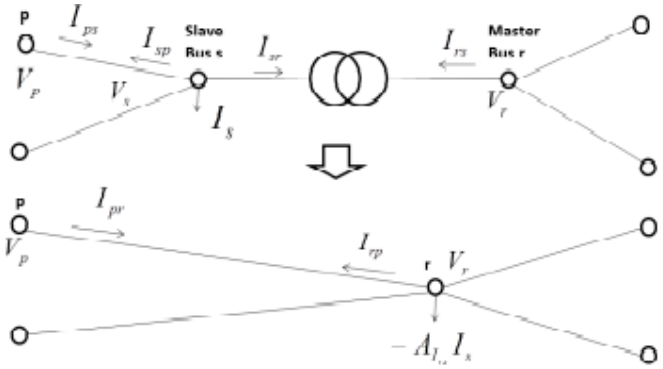


Figure 3. Model of a zero-impedance branch

Smart Meter Data Analysis for Power Theft Detection

Citation: Nikovski, D.N.; Wang, Z.; Esenther, A.; Sun, H.; Sugiura, K.; Muso, T.; Tsuru, K., "Smart Meter Data Analysis for Power Theft Detection", *International Conference on Machine Learning and Data Mining in Pattern Recognition (MLDM)*, ISBN: 867030542038611-0, pp. 379-389, July 2013

Contacts: Daniel Nikovski, Hongbo Sun

We propose a method for power theft detection based on predictive models for technical losses in electrical distribution networks estimated entirely from data collected by smart meters in smart grids. Although the data sampling rate of smart meters is not sufficiently high to detect power theft with complete certainty, detection is still possible in a statistical decision theory sense, based on statistical models estimated from collected data sets. Even without detailed knowledge of the exact topology of the distribution network, it is possible to estimate a statistical model of the technical losses that allows indirect estimation of the non-technical losses (power theft) with high accuracy.

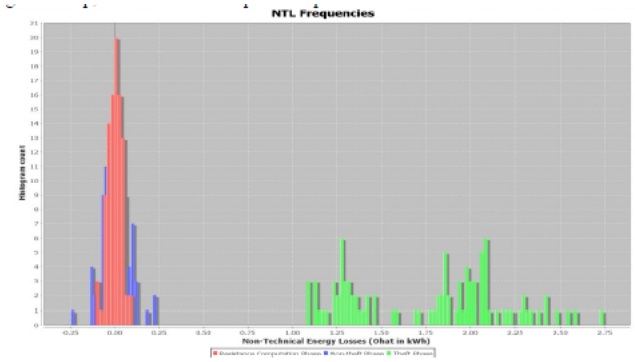


Fig. 6. Histograms for NTL estimates during three testing intervals (phases). In red, NTL estimates are shown for the interval from which the predictive model for technical losses was constructed. In blue, NTL estimates are shown for the second interval during which no theft was present. In green, NTL estimates are shown for the last interval during which theft did occur.

Semismooth Equation Approach to Network Utility Maximization (NUM)

Citation: Bai, L.; Raghunathan, A.U., "Semismooth Equation Approach to Network Utility Maximization (NUM)", *American Control Conference (ACC)*, ISBN: 978-1-4799-0177-7, ISSN: 0743-1619, pp. 4795-4801, June 2013

Contacts: Arvind Raghunathan

Recently there has been investigation of barrier methods for the solution of NUM which have been shown to possess second order convergence. However, the question of accelerating dual decomposition based methods is still open. We propose a novel semi-smooth equation approach to solving the standard dual decomposition formulation of NUM. We show that under fairly mild assumptions that the approach converges locally super-linearly to the solution of the NUM. Globalization of the proposed algorithm using a line search is also described.

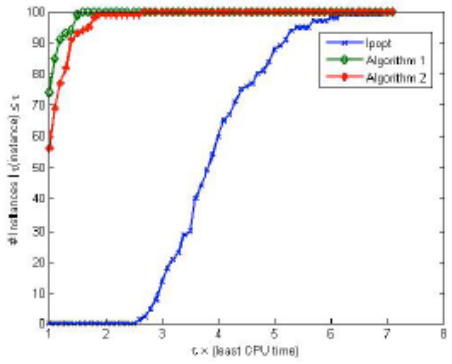


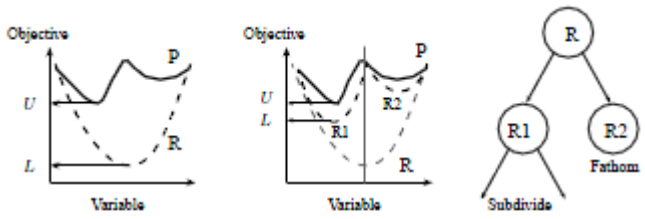
Fig. 4. Performance profiles of algorithms based on CPU time for convergence.

Global Optimization of Multi-Period Optimal Power Flow

Citation: Gopalakrishnan, A.; Raghunathan, A.U.; Nikovski, D.N.; Biegler, L.T., "Global Optimization of Multi-period Optimal Power Flow", *American Control Conference (ACC)*, ISBN: 978-1-4799-0177-7, ISSN: 0743-1619, pp. 1157-1164, June 2013

Contacts: Arvind Raghunathan, Daniel Nikovski

In this work, we solve multi-period optimal power flow (MOPF) problems determining global optimality. The multi-period version of the OPF is time coupled due to the integration of storage systems into the network, and ramp constraints on the generators. The global optimization algorithm is based on the spatial branch and bound framework with lower bounds on the optimal objective function value calculated by solving a semi definite programming (SDP) relaxation of the MOPF. The proposed approach does not assume convexity and is more general than the ones presented previously for the solution of MOPF. We present a case study of the IEEE 57 bus instance with a time varying demand profile. The integration of storage in the network helps to satisfy loads during high demands and the ramp constraints ensure smooth generation profiles. The SDP relaxation does not satisfy the rank condition, and our optimization algorithm is able to guarantee global optimality within reasonable computational time.



(a) Lower and Upper Bounding (b) Domain Subdivision (c) Search tree

Fig. 1: Branch and Bound Schematic

A Method for Computing Optimal Set-Point Schedules for HVAC Systems

Citation: Nikovski, D.N.; Xu, J.; Nonaka, M., "A Method for Computing Optimal Set-Point Schedule for HVAC Systems", *REHVA World Congress (CLIMA)*, June 2013

Contacts: Daniel Nikovski

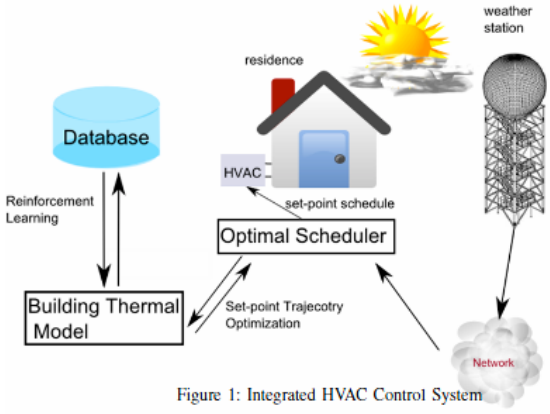


Figure 1: Integrated HVAC Control System

We propose a method for model-based control of building air conditioning systems that minimizes energy costs while maintaining occupant comfort. The method uses a building thermal model in the form of a thermal circuit identified from collected sensor data, and reduces the building thermal dynamics to a Markov decision process (MDP) whose decision variables are the sequence of temperature set-points over a suitable horizon, for example one day. The main advantage of the resulting MDP model is that it is discrete, which allows for a very fast computation of the optimal sequence of temperature set-points. Experiments on thermal models demonstrate savings that can exceed 50% with respect to usual control strategies in buildings such as night setup.

Operational Planning of Thermal Generators with Factored Markov Decision Process Models

Citation: Nikovski, D.N., "Operational Planning of Thermal Generators with Factored Markov Decision Process Models", *International Conference on Automated Planning and Scheduling (ICAPS)*, June 2013

Contacts: Daniel Nikovski

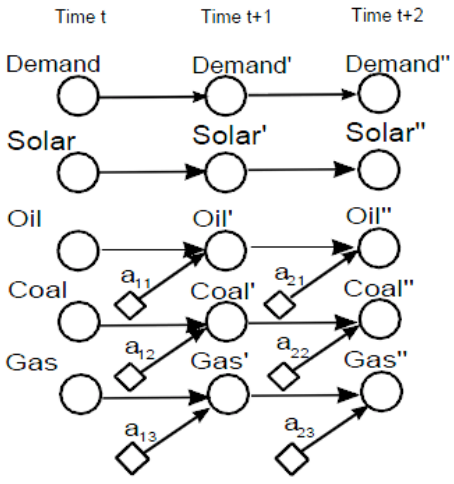


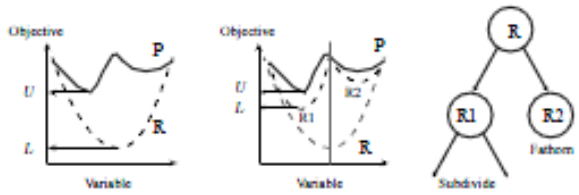
Figure 1: DBN for a power generation problem with three controllable and one uncontrollable power generators.

We describe a method for creating conditional plans for controllable thermal power generators operating together with uncontrollable renewable power generators, under significant uncertainty in demand and output. The resulting stochastic sequential decision problem has mixed discrete and continuous state variables and dynamics, and we propose a discretization method for the continuous part of the model that unifies all variables into a large discrete Markov decision process model. Although this model is way too large to be solved directly, its state transition probabilities can be factored efficiently, and a reduction of all continuous variables to one net demand variable makes it tractable by dynamic programming over a suitably constructed AND/OR tree. The proposed algorithm outperformed existing non-stochastic solvers on several problem instances.

Global Optimization of Optimal Power Flow Using a Branch & Bound Algorithm

Citation: Gopalakrishnan, A.; Raghunathan, A.U.: Nikovski, D.; Biegler, L.T., "Global Optimization of Optimal Power Flow Using a Branch & Bound Algorithm", *Allerton Conference on Communication, Control, and Computing*, October 2012

Contacts: Arvind U. Raghunathan, Daniel N. Nikovski



(a) Lower and Upper Bounding (b) Domain Subdivision (c) Search tree

Fig. 1: Branch and Bound Schematic

We propose two algorithms for the solution of the Optimal Power Flow (OPF) problem to global optimality. The algorithms are based on the spatial branch and bound framework with lower bounds on the optimal objective function value calculated by solving either the Lagrangian dual or the semidefinite programming (SDP) relaxation. We show that this approach can solve to global optimality the general form of the OPF problem including: generation power bounds, apparent and real power line limits, voltage limits and thermal loss limits. The approach makes no assumption on the topology or resistive connectivity of the network. We present the performance of the algorithms on a number of standard IEEE systems, which are known to have a zero duality gap.

Envisioning Grid Vulnerabilities: Multi-dimensional Visualization for Electrical Grid Planning

Citation: Romero, R.; Diez, D.; Wittenburg, K.; Diaz, P., "Envisioning Grid Vulnerabilties: Multi-dimensional Visualization for Electrical Grid Planning", *International Working Confereance on Advanced visual Interfaces (AVI),* ISBN: 978-1-4503-1287-5, pp. 701-704, May 2012

Contacts: Kent B. Wittenburg

Figure 4. Screen shot of BarExam software. View is filtered following Figure 3 selections. Detailed view of the Element_code dimension shows co-occurrence through vertical alignment with the elements ordered by frequency.

Electrical grid planning aims at optimizing the grid through the control of the performance and placement of electrical assets in order to minimize failures or vulnerabilities. With this purpose, grid planners carry out an initial stage of data exploration using a large volume of incident and equipment data collected over extensive time periods. In current practice these tasks are performed manually, which makes it very difficult to recognize patterns and gain insights into the data. In this paper, we propose a parallel multivariate visualization technique as a suitable approach for improving the existing practice. Based on the usage of an interactive visualization tool called BarExam, we demonstrate the feasibility of this visualization technique for displaying the dataset and present example insights that this visualization techniques can provide to grid planners.

Spatial Analysis

The research in the Spatial Analysis group at MERL covers all aspects of extracting information from images. For instance, from a picture of a scene we can compute features that allow the detection and location of specific objects. Or we learn a dictionary for the appearance of local patches in an image and use it to classify regions and objects or to improve the image quality. We can track a moving object in video to quantify its trajectory. In some cases we can modify the actual image creation process to make subsequent information extraction more effective. For instance, multiple flash exposures can be used to identify an object's edges.

Several of our current projects involve 3D analysis based on 2D images. For example, we have developed algorithms for estimation of object pose so that a robot arm can grasp an object from a cluttered workspace. In another project, we infer automobile position in a city through matching of camera images to a 3D city model. For medical radiation treatment, we align patient position by matching current x-rays to simulated x-rays obtained by project. In all these cases, the algorithms we have developed must be very fast and accurate. We have also developed algorithms that operate directly on 3D data for reconstruction, detection, and recognition.

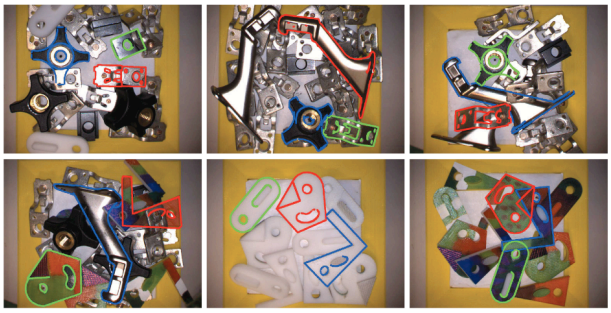
For several years, MERL has been a leader in computational photography and Spatial Analysis. Given that many images are now computer processed prior to viewing, this research seeks to modify the capture stage to optimize the information transfer into the computer and ultimately into the final usage-perhaps human viewing, or perhaps more computer analysis to extract quantitative measures from the image. In this research MERL has been able to dramatically improve corrections for motion and focus blur, achieve spatial and temporal super-resolution in video, and conceive novel camera optics for wide field of view stereo reconstruction.

Recent Research

Fast Object Localization and Pose Estimation in Heavy Clutter for Robotic Bin Picking

Citation: Liu, M.-Y.; Tuzel, O.; Veeraraghavan, A.; Taguchi, Y.; Marks, T.K.; Chellappa, R., "Fast Object Localization and Pose Estimation in Heavy Clutter for Robotic Bing Picking", *The International Journal of Robotics Research*, May 2012

Contacts: Ming-Yu Liu, Tim K. Marks, Yuichi Taguchi, C. Oncel Tuzel

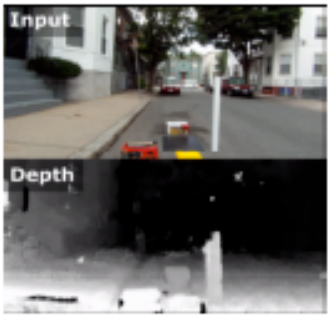


We present a practical vision-based robotic bin-picking system that performs detection and 3D pose estimation of objects in an unstructured bin using a novel camera design, picks up parts from the bin, and performs error detection and pose correction while the part is in the gripper. Two main innovations enable our system to achieve real-time robust and accurate operation. First, we use a multi-flash camera that extracts robust depth edges. Second, we introduce an efficient shape-matching algorithm called fast directional chamfer matching (FDCM), which is used to reliably detect objects and estimate their poses. FDCM improves the accuracy of chamfer matching by including edge orientation. It also achieves massive improvements in matching speed using line-segment approximations of edges, a 3D distance transform, and directional integral images. FDCM is up to two orders of magnitude faster than the previous methods.

Monocular Visual Odometry and Dense 3D Reconstruction for On-Road Vehicles

Citation: Zhu, M.; Ramalingam, S.; Taguchi, Y.; Garaas, T.W., "Monocular Visual Odometry and Dense 3D Reconstruction for On-Road Vehicles", *European Conference on Computer Vision (ECCV)*, Vol. 7584, 2012, pp. 596-606, October 2012

Contacts: Srikumar Ramalingam, Tyler W. Garaas, Yuichi Taguchi



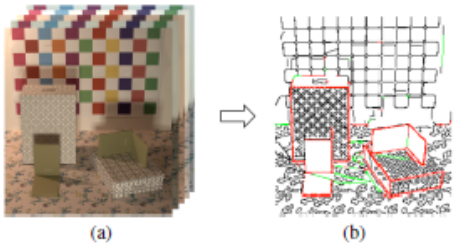
(c)

More and more on-road vehicles are equipped with cameras each day. This paper presents a novel method for estimating the relative motion of a vehicle from a sequence of images obtained using a single vehicle-mounted camera. In this paper, we show that the planar 2-point motion estimation can be solved analytically using a single quadratic equation. Although 2-point motion estimation generates visually accurate on-road vehicle-trajectory, the motion is not precise enough to perform dense 3D reconstruction due to the non-planarity of roads. Thus we use a 2-point relative motion algorithm for the initial images followed by 3-point 2D-to-3D camera pose estimation for the subsequent images. Using this hybrid approach, we generate accurate motion estimates for a plane-sweeping algorithm that produces dense depth maps for obstacle detection applications.

Detecting 3D Geometric Boundaries of Indoor Scenes Under Varying Lighting

Citation: Ni, J.; Marks, T.K.; Tuzel, C.O.; Porikli, F., "Detecting 3D Geometric Boundaries of Indoor Scenes Under Varying Lighting", *IEEE Winter Conference on Applications of Computer Vision (WACV)*, March 2014

Contacts: Tim Marks, Oncel Tuzel



(a) (b)

Figure 1. Problem overview: Given a set of images of a static indoor scene under varying lighting (a), we identify 3D geometric boundaries (shown in red) and shadow edges (shown in green), as opposed to texture edges (shown in black) (b).

The goal of this research is to identify 3D geometric boundaries in a set of 2D photographs of a static indoor scene under unknown, changing lighting conditions. 3D geometric boundaries can be used effectively for reasoning about the 3D layout of a scene. To distinguish 3D geometric boundaries from 2D texture edges, we analyze the illumination subspace of the local appearance at each image location. In indoor time-lapse photography and surveillance video, we frequently see images that are lit by unknown combinations of uncalibrated light sources. We introduce an algorithm for semi-binary nonnegative matrix factorization (SBNMF) to decompose such images into a set of lighting basis images, each of which shows the scene lit by a single light source.

Point-Plane SLAM for Hand-Held 3D Sensors

Citation: Taguchi, Y.; Jian, Y-D; Ramalingam, S.; Feng, C., **"Point-Plane SLAM for Hand-Held 3D Sensors"**, *IEEE International Conference on Robotics and Automation (ICRA)*, DOI: 10.1109/ICRA.2013.6631318, ISSN: 1050-4729, ISBN: 978-1-4673-5641-1, pp. 5182-5189, May 2013

Contacts: Yuichi Taguchi, Srikumar Ramalingam

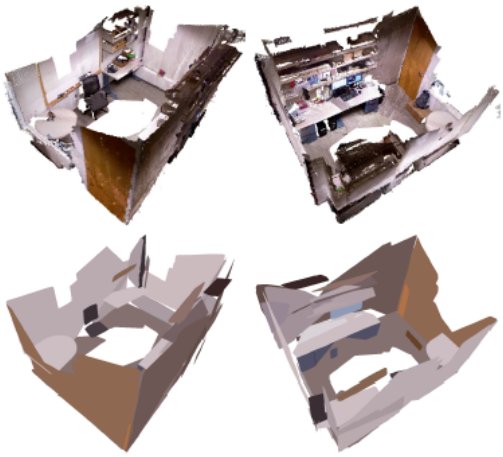


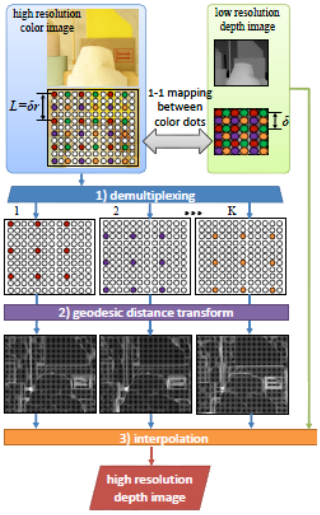
Fig. 1. A 3D model reconstructed from the sequence in Figure 4. Our system not only generates registered 3D point clouds (top), but also reconstructs a scene as a set of planes (bottom). Note that the plane-based model is obtained from plane landmarks, which are generated by our SLAM system in real time, not in post-processing. In this model, the number of keyframes registered is 86, and the numbers of point and plane landmarks are 17290 and 32, respectively.

We present a simultaneous localization and mapping (SLAM) algorithm for a hand-held 3D sensor that uses both points and planes as primitives. We show that it is possible to register 3D data in two different coordinate systems using any combination of three point/plane primitives (3 planes, 2 planes and 1 point, 1 plane and 2 points, and 3 points). In contrast to existing approaches that mainly use points for registration, our algorithm has the following advantages: (1) it enables faster correspondence search and registration due to the smaller number of plane primitives; (2) it produces plane-based 3D models that are more compact than point-based ones; and (3) being a global registration algorithm, our approach does not suffer from local minima or any initialization problems. Our experiments demonstrate real-time, interactive 3D reconstruction of indoor spaces using a hand-held Kinect sensor.

Joint Geodesic Upsamping of Depth Images

Citation: Liu, M-Y; Tuzel, C.O.; Taguchi, Y., "Joint Geodesic Upsampling of Depth Images", *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, DOI: 10.1109/CVPR.2013.29, ISSN: 1063-6919, pp. 169-176, June 2013

Contacts: Ming-Yu Liu, Oncel Tuzel, Yuichi Taguchi



We propose an algorithm utilizing geodesic distances to upsample a low resolution depth image using a registered high resolution color image. Specifically, it computes depth for each pixel in the high resolution image using geodesic paths to the pixels whose depths are known from the low resolution one. Though this is closely related to the all-pairshortest-path problem which has O(n2 log n) complexity, we develop a novel approximation algorithm whose complexity grows linearly with the image size and achieve realtime performance. We compare our algorithm with the state of the art on the benchmark dataset and show that our approach provides more accurate depth upsampling with fewer artifacts. In addition, we show that the proposed algorithm is well suited for upsampling depth images using binary edge maps, an important sensor fusion application.

A Theory of Minimal 3D Point to 3D Plane Registration and Its Generation

Citation: Ramalingam, S.; Taguchi, Y., "A Theory of Minimal 3D Point to 3D Plane Registration and Its Generalization", *International Journal of Computer Vision,* DOI: 10.1007/s11263-012-0476-x, September 2012

Contacts: Srikumar Ramalingam, Yuichi Taguchi

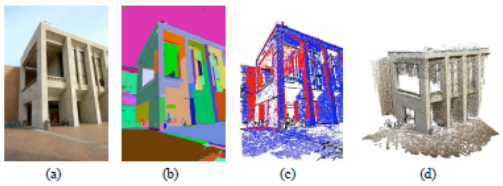


Fig. 7. Registering two point clouds, each generated by applying multi-view reconstruction techniques to 15 images. (a) One of the images used in 3D reconstruction. (b) superpixel segmentation of the image shown in (a). (c) The 3D points from the first (blue) and second (red) clouds are reprojected onto the superpixel image. The points from the first point cloud are used to compute the superpixel plane parameters, while the second point cloud is preserved as points. The correspondence between the points from the second cloud and the planes obtained from the first cloud are determined by the underlying superpixel. (d) 3D model after merging the two partial reconstructions from the two clusters. **[Best viewed in color]**

Registration of 3D data is a key problem in many applications in computer vision, computer graphics and robotics. This paper provides a family of minimal solutions for the 3D-to-3D registration problem in which the 3D data are represented as points and planes. Such scenarios occur frequently when a 3D sensor provides 3D points and our goal is to register them to a 3D object represented by a set of planes. To compute the 6-degrees-of-freedom transformation between the sensor and the object, we need at least six points on three or more planes. We systematically investigate and develop pose estimation algorithms for several configurations, including all minimal configurations that arise from the distribution of points on planes. We show that many 2D-to-3D and 3D-to-3D pose estimation/registration algorithms involving points, lines, and planes can be mapped to the proposed framework. We validate our theory in simulations as well as in three real-world applications: registration of a robotic arm with an object using a contact sensor, registration of planar city models with 3D point clouds obtained using multi-view reconstruction, and registration between depth maps generated by a Kinect sensor.

A Theory of Multi-Layer Flat Refractive Geometry

Citation: Agrawal, A.; Ramalingam, S.; Taguchi, Y.; Chari, V., "A Theory of Multi-Layer Flat Refractive Geometry", *IEEE Conference on Computer Vision and Pattern Recognition (CVPR),* pp. 3346-3353, June 2012

Contacts: Amit K. Agrawal, Srikumar Ramalingam, Yuichi Taguchi

Figure 6. (Left) Setup. (Right) Photo captured by looking through a water tank. Projected 3D points are overlayed by applying pose estimated using CA (green) and our algorithm (red).

Flat refractive geometry corresponds to a perspective camera looking through single/multiple parallel flat refractive mediums. We show that the underlying geometry of rays corresponds to an axial camera. This realization, missing from previous works, leads us to develop a general theory of calibrating such systems using 2D-3D correspondences. The pose of 3D points is assumed to be unknown and is also recovered. Calibration can be done even using a single image of a plane. We show that the unknown orientation of the refracting layers corresponds to the underlying axis, and can be obtained independently of the number of layers, their distances from the camera and their refractive indices. Interestingly, the axis estimation can be mapped to the classical essential matrix computation and the 5-point algorithm can be used. After computing the axis, the thicknesses of layers can be obtained linearly when refractive indices are known, and we derive analytical solutions when they are unknown.

Sensor Placement Tool for Rapid Development of Video Sensor Layouts

Citation: Garaas, T.W., "Sensor Placement Tool for Rapid Development of Video Sensor Layouts", *Symposium on Simulation for Architecture and Urban Design (SimAUD)*, pp. 134-137, April 2011

Contacts: Tyler W. Garaas

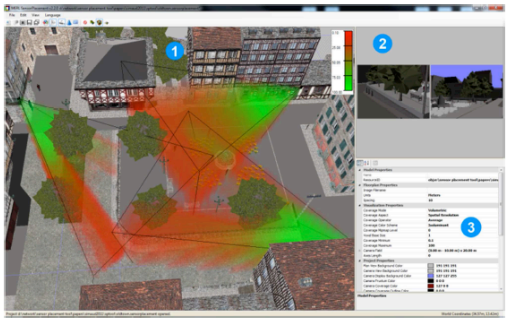


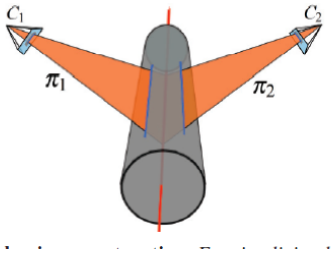
Figure 1. Illustration of the SPtool GUI and the components that comprise it. Component 1 is the primary view window, where users interact with the environment and video sensors. Component 2 provides a virtual view from sensors within the environment. Finally, component 3 is a properties grid, where users can customize the parameters of selected 3D models, selected video sensors, environment parameters, or the sensor coverage analysis and visualization.

The arrangement of video sensors—in closed circuit television (CCTV) systems, for instance—can have drastic effects on the efficiency and cost of the final system. In the present work, I describe a tool designed for rapid construction of simulated video sensor layouts that allows quantification of sensor coverage and cost estimation to be determined prior to installation; thus, avoiding costly changes during or after the installation. Most previous work in this area either considers sensor coverage only in a 2D space or requires significant preparation to achieve accurate results in 3D. In the present work, I describe an implementation of a novel coverage-analysis algorithm that uses the geometry of image formation to cast rays from simulated video sensors through the monitored area to estimate sensor coverage at every 3D location. Visualization techniques of the acquired sensor coverage data are additionally presented.

Find a Needle in a Specular Haystack

Citation: Shroff, N.; Taguchi, Y.; Tuzel, O.; Veeraraghavan, A.; Ramalingam, S.; Okuda, H., "Finding a Needle in a Specular Haystack", *IEEE International Conference on Robotics and Automation (IRCA)*, DOI: 10.1109/ICRA.2011.5979857, pp. 5963-5970, May 2011

Contacts: Yuichi Taguchi, Takaaki Sakaguchi, C. Oncel Tuzel

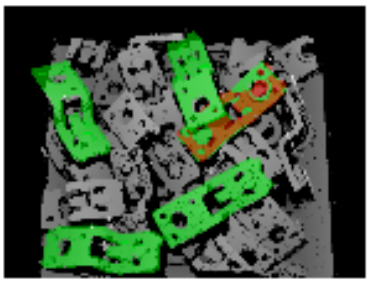


Progress in machine vision algorithms has led to widespread adoption of these techniques to automate several industrial assembly tasks. Nevertheless, shiny or specular objects which are common in industrial environments still present a great challenge for vision systems. In this paper, we take a step towards this problem under the context of vision-aided robotic assembly. We show that when the illumination source moves, the specular highlights remain in a region whose radius is inversely proportional to the surface curvature. This allows us to extract regions of the object that have high surface curvature. These points of high curvature can be used as features for specular objects. Further, an inexpensive multi-flash camera (MFC) design can be used to reliably extract these features. We show that one can use multiple views of the object using the MFC in order to triangulate and obtain the 3D location and pose of the shiny objects. Finally, we show a system consisting of a robot arm with an MFC that can perform automated detection and pose estimation of shiny screws within a cluttered bin, achieving position and orientation errors less than 0.5 mm and 0.8 respectively.

Voting-based Pose Estimation for Robotic Assembly Using a 3D Sensor

Citation: Choi, C.; Taguchi, Y.; Tuzel, O.; Liu, M.-Y.; RAmalingam, S., "Voting-based Pose Estimation for Robotic Assembly Using a 3D Sensor", *IEEE International Conference on Robotics and Automation (ICRA)*, DOI: 10.1109/ICRA.2012.6225371, pp. 1724-1731, May 2012

Contacts: Yuichi Taguchi, Ming-Yu Liu, Srikumar Ramalingam, C. Oncel Tuzel



We propose a voting-based pose estimation algorithm applicable to 3D sensors. It was recently shown that a pair of oriented 3D points, which are points on the object surface with normals, in a voting framework enables fast and robust pose estimation. Although oriented surface points are discriminative for objects with sufficient curvature changes, they are not compact and discriminative enough for many industrial and real-world objects that are mostly planar. As edges play the key role in 2D registration, depth discontinuities are crucial in 3D. In this paper, we investigate and develop a family of pose estimation algorithms that better exploit this boundary information. In addition to oriented surface points, we use two other primitives: boundary points with directions and boundary line segments. Our experiments show that these carefully chosen primitives encode more information compactly and thereby provide higher accuracy for a wide class of industrial parts and enable faster computation.

Entropy-Rate Clustering: Cluster Analysis via Maximizing a Submodular Function Subject to a Matroid Constraint

Citation: Liu, M-Y; Tuzel, C.O.; Ramalingam, S.; Chellappa, R., "Entropy-Rate Clustering: Cluster Analysis via Maximizing a Submodular Function Subject to a Matroid Constraint", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, DOI: 10.1109/TPAMI.2013.107, ISSN: 0162-8828, Vol. 36, Issue 1, pp. 99-112, January 2014

Contacts: Ming-Yu Liu, Oncel Tuzel, Srikumar Ramalingam

Fig. 9. Superpixel segmentation examples. The images contain 100 superpixels. The ground truth segments are color-coded and blended on the images. The superpixels (boundaries shown in white) respect object boundaries and tend to divide an image into similar-sized regions.

We propose a new objective function for clustering consisting of two components: the entropy rate of a random walk on a graph and a balancing term. The entropy rate favors formation of compact and homogeneous clusters, while the balancing function encourages clusters with similar sizes and penalizes larger clusters that aggressively group samples. We present a novel graph construction for the graph associated with the data and show that this construction induces a matroid — a combinatorial structure that generalizes the concept of linear independence in vector spaces. We validate the proposed algorithm on various benchmarks and show its competitive performance with respect to popular clustering algorithms.

Pose Normalization via Learned 2D Warping for Fully Automatic Face Recognition

Citation: Asthana, A.; Jones, M.J.; Marks, T.K.; Tieu, K.H.; Goecke, R., "Pose Normalization via Learned 2D Warping for Fully Automatic Face Recognition", *British Machine Vision Conference (BMVC)*, August 2011

Contacts: Michael J. Jones, Tim K. Marks

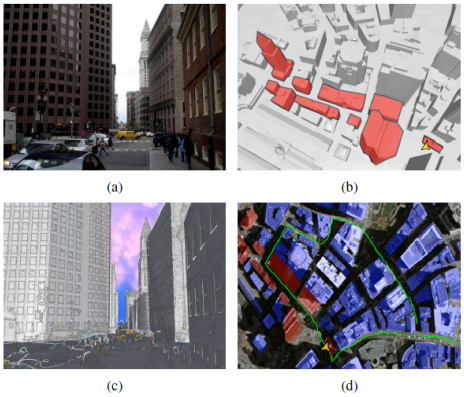
Figure 3: Overview of our fully automatic pose-invariant face recognition system.

We present a novel approach to pose-invariant face recognition that handles continuous pose variations, is not database-specific, and achieves high accuracy without any manual intervention. Our fully automatic system for face recognition includes automatic methods for extracting 2D facial feature points and accurately estimating 3D head pose, and this information is used as input to the 2D pose-normalization algorithm. The current system can handle pose variation up to 45 degrees to the left or right (yaw angle) and up to 30 degrees up or down (pitch angle). The system demonstrates high accuracy in experiments on the CMU-PIE, USF 3D, and Multi-PIE databases, convincingly outperforming other automatic methods.

Pose Estimation using Both Points and Lines for Geo-Localization

Citation: Ramalingam, S.; Bouazia, S.; Sturm, P., "Pose Estimation using Both Points and Lines for Geo-Localization", *IEEE International Conference on Robotics and Automation (ICRA)*, DOI: 10.1109/ICRA.2011.5979781, pp. 4716-4723, May 2011

Contacts: Srikumar Ramalingam



This paper identifies and fills the probably last two missing items in minimal pose estimation algorithms using points and lines. Pose estimation refers to the problem of recovering the pose of a calibrated camera given known features (points or lines) in the world and their projections on the image. There are four minimal configurations using point and line features: 3 points, 2 points and 1 line, 1 point and 2 lines, 3 lines. The first and the last scenarios that depend solely on either points or lines have been studied a few decades earlier. However the mixed scenarios, which are more common in practice, have not been solved yet. In this paper we show that it is indeed possible to develop a general technique that can solve all four scenarios. The centerpiece of our method is a simple and generic method that uses collinearity and coplanarity constraints for solving the pose.

Manhattan Junction Catalogue for Spatial Reasoning of Indoor Scenes

Citation: Ramalingam, S.; Pillai, J.K.; Jain, A.; Taguchi, Y., "Manhattan Junction Catalogue for Spatial Reasoning of Indoor Scenes", *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, DOI: 10.1109/CVPR. 2013. 394, ISSN: 1063-6919, pp. 3065-3072, June 2013

Contacts: Srikumar Ramalingam, Yuichi Taguchi

Figure 1. *A living room with several junctions of types* **L**, **T**, **Y**, **X** *and* **W**. *We present a novel method to detect these junctions and use them for recovering the spatial layout of a scene.*

In this paper, we consider the problem of detecting junctions and using them for recovering the spatial layout of an indoor scene. We work in a constrained Manhattan world setting where the junctions are formed by only line segments along the three principal orthogonal directions. Junctions can be classified into several categories based on the number and orientations of the incident line segments. We provide a simple and efficient voting scheme to detect and classify these junctions in real images. Indoor scenes are typically modeled as cuboids and we formulate the problem of the layout estimation as an inference problem in a conditional random field. Our formulation allows the incorporation of junction features and the training is done using structured prediction. We outperform other single view geometry estimation methods on standard datasets.

Mechatronics

The Mechatronics group conducts fundamental and applied research and develops advanced control technology for mechatronic systems. Mechatronics (mechanics + electronics) is a multidisciplinary field of engineering science combines mechanical engineering, electrical engineering, control engineering, dynamical systems and embedded computer systems. The Mechatronics Group has expertise in multivariable, nonlinear, optimal & model-predictive control theory, nonlinear estimation, nonlinear dynamical systems, mechanical design, laser processing and sensing, 3D CAD and rapid prototyping. The business drivers for this R&D program are twofold. First, control of mechatronic systems is central to many areas of Mitsubishi Electric's business. Second, with the increasing power and decreasing cost of embedded computation and sensing technologies, there is the opportunity for innovation and synergy among researchers in the Mechatronics Group and other researchers in MERL's other research groups whose strengths include signal processing, computer and information technology.

Automatic control systems take real-time measurements of a system under control, process the information with a control algorithm, and apply the results of the calculation back to the system under control via actuators. MERL's research focuses on development of new control algorithms that provide higher performance than the state-of-the-art. Recent results include more energy efficient air conditioners and servomotors, more precise laser processing systems, smoother riding elevators, and low-fuel mission plans for space probes. MERL also conducts fundamental research to develop new control theory for general-purpose use, with a strong focus on model predictive an adaptive control theory.

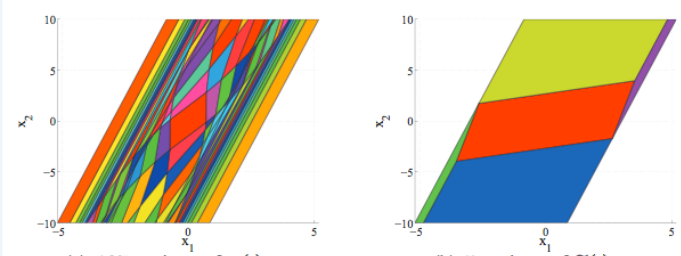
A dynamical system is one described by differential or difference equations. MERL's interest is to improve the performance of MELCO products and technology through the application of nonlinear dynamical systems theory. Applied research interests include mixing in fluids and the design of minimum-fuel trajectories for space probes, both of which exploit nonlinearity and chaos in highly creative and deeply mathematical ways.

Recent Research

Nearly-Optimal Simple Explicit MPC Regulators with Recursive Feasibility Guarantees

Citation: Takacs, B.; Holaza, J.; Kvasnica, M.; Di Cairano, S., "Nearly-Optimal Simple Explicit MPC Regulators with Recursive Feasibility Guarantees", *IEEE Conference on Decision and Control (CDC)*, DOI: 10.1109/CDC.2013.6761013, ISSN: 0743-1546, pp. 7089-7094, December 2013

Contacts: Stefano Di Cairano

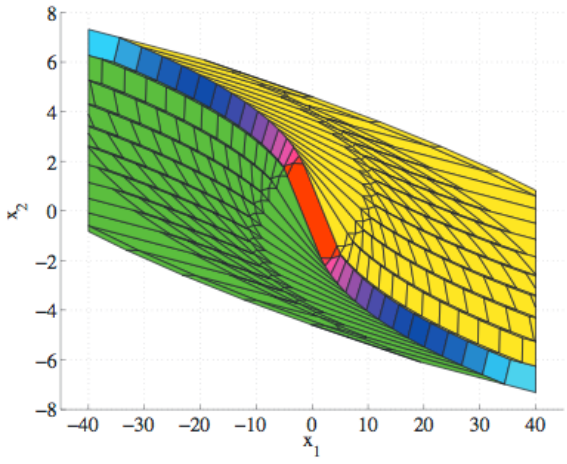

(a) 127 regions of $\mu(\cdot)$. (b) 5 regions of $\widetilde{\mu}(\cdot)$.

Explicit Model Predictive Control (MPC) is an attractive control strategy, especially when one aims at a fast, computationally less demanding implementation of MPC. Although leading to a fast implementation of optimization-based control, the main downside of explicit MPC is its high complexity in terms of memory occupancy, which often limits its practical applicability. In this paper we obtain simple explicit MPC controllers that provide guarantees of recursive satisfaction of input and state constraints. The task is accomplished by optimizing, off-line, the parameters of the feedback law such that an integrated square error between the optimal, but complex controller and its simpler replacement is minimized.

Polygonic Representation of Explicit Model Predictive Control

Citation: Oravec, J.; Blazek, S.; Kvasnica, M.; Di Cairano, S., "Polygonic Representation of Explicit Model Predictive Control", *IEEE Conference on Decision and Control (CDC)*, DOI: 10.1109/CDC.2013.6760905, ISSN: 0743-1546, pp. 6422-6427, December 2013

Contacts: Stefano Di Cairano

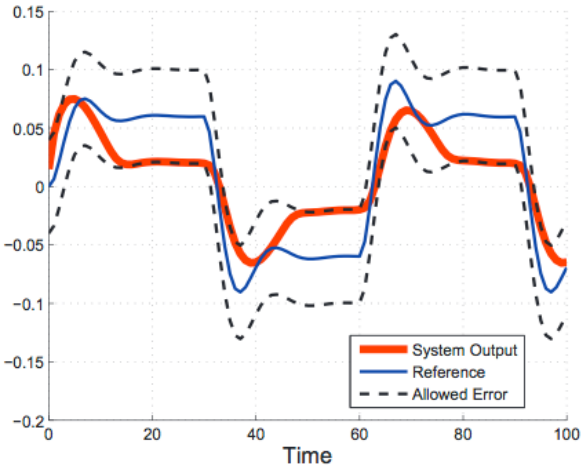


The paper proposes to reduce complexity of explicit MPC feedback laws by representing regions over which the law is defined as (possibly non-convex) polygons. Each polygon is then represented only by its boundaries, which reduces the memory footprint of the feedback law. Even though significant amount of memory can be saved this way, the price to be paid is increased computational load associated by performing point location tasks in non-convex objects. Therefore we propose to devise inner and outer convex approximations of non-convex polygons to reduce the computational requirements. Such approximations allow performing point location more effectively, leading to a reduction of the required on-line computational effort. Several ways to design suitable approximations are presented and efficacy of the proposed procedure is evaluated.

Constrained Tracking with Guaranteed Error Bounds

Citation: Di Cairano, S.; Borrelli, F., "Constrained Tracking with Guaranteed Error Bounds", *IEEE Conference on Decision and Control (CDC)*, DOI: 10.1109/CDC. 2013.6760469, ISSN: 0743-1548,pp. 3800-3805, December 2013

Contacts: Stefano Di Cairano



We study the problem of tracking a time-varying reference signal for constrained linear systems. The reference signal is the output of a linear system driven by an unknown bounded input. The goal is to track the reference signal and never violate a predefined tracking error bound. The paper presents the design of a reference tracking controller satisfying state and input constraints and guaranteeing the desired tracking error bound for all admissible reference signals. A model predictive controller (MPC) enforcing a robust invariant set is employed. We show how to compute the robust invariant set and how to design the tracking MPC law which guarantees constraints satisfaction and persistent feasibility. Simulations show the effectiveness of the proposed approach.

On a Multiplicative Update Dual Optimization Algorithm for Constrained Linear MPC

Citation: Di Cairano, S.; Borrelli, F., "Constrained Tracking with Guaranteed Error Bounds", *IEEE Conference on Decision and Control (CDC)*, DOI: 10.1109/CDC. 2013.6760469, ISSN: 0743-1548,pp. 3800-3805, December 2013

Contacts: Stefano Di Cairano, Matthew Brand

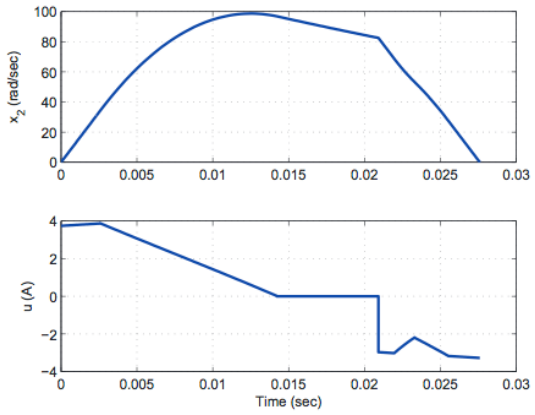
Solver	Avg[ms]	Min[ms]	Max[ms]
GPADM:	46.567	0.222	196.481
PQPM:	11.515	0.319	42.618
QUADPROG:	2.954	1.462	7.948
QPACT:	0.597	0.445	0.986
NAG:	0.917	0.615	1.387
PQPMEX:	0.937	0.069	3.553
PQPMPC:	0.444	0.032	1.985

TABLE I: Computation time for the aircraft example.

We discuss a multiplicative update quadratic programming algorithm with applications to model predictive control for constrained linear systems. The algorithm, named PQP, is very simple to implement and thus verify, does not require projection, offers a linear rate of convergence, and can be completely parallelized. The PQP algorithm is equipped with conditions that guarantee the desired bound on sub optimality and with an acceleration step based on projection-free line search. We also show how PQP can take advantage of the parametric structure of the MPC problem, thus moving offline several calculations and avoiding large input/output data flows. The algorithm is evaluated on two benchmark problems, where it is shown to compete with, and possibly outperform, other open source and commercial packages.

A Hamiltonian Approach to Compute an Energy Efficient Trajectory for a Servomotor System

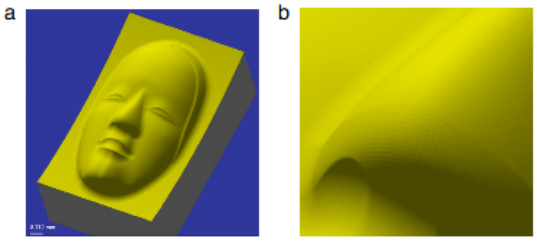
Citation: Wang, Y.; Ueda, K.; Bortoff, S.A., "A Hamiltonian Approach to Compute an Energy Efficient Trajectory for a Servomotor System", *Automatica*, DOI: 10.1016/ j.automatica.2013.09.019, Vol. 49, Issue 12, pp. 3550-3561, Dec 2013
Contacts: Yebin Wang, Scott Bortoff



This paper considers a nonlinear constrained optimal control problem (NCOCP) originated from energy optimal trajectory planning of servomotor systems. Solving the exact optimal solution is challenging because of the nonlinear and switching cost function, and various constraints. This paper proposes a method to manage the switching cost function to establish a set of necessary conditions of an NCOCP. Specifically, a concept "sub-trajectory" is introduced to match multiple Hamiltonians due to switches in the cost function. Necessary conditions on the optimal trajectory are established as a union of conditions for all sub-trajectories and Weierstrass-Erdmann corner conditions between sub-trajectories. A decomposition-based shooting method is proposed to compute an optimal trajectory by solving multi-point boundary value problems. Simulations and experiments validate the effectiveness of the methodology and the energy saving benefit.

High Accuracy NC Milling Simulation Using Composite Adaptively Sampled Distance Fields

Citation: Sullivan, A.; Erdim, H.; Perry, R.N.; Frisken, S.F., "High Accuracy NC Milling Simulation Using Composite Adaptively Sampled Distance Fields", Computer-Aided Design, Vol. 44, Issue 6, pp. 522-536, June 2012
Contacts: Alan Sullivan, Ronald N. Perry

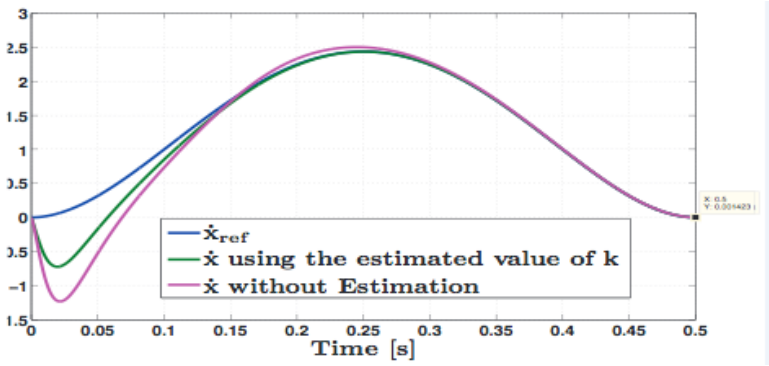


We describe a new approach to shape representation called a composite adaptively sampled distance field (composite ADF) and describe its application to NC milling simulation. In a composite ADF each shape is represented by an analytic or procedural signed Euclidean distance field and the milled workpiece is given as the Boolean difference between distance fields representing the original workpiece volume and distance fields representing the volumes of the milling tool swept along the prescribed milling path. The computation of distance field of the swept volume of a milling tool is handled by an inverted trajectory approach where the problem is solved in tool coordinate frame instead of a world coordinate frame.

Nonlinear Adaptive Control for Electromagnetic Actuators

Citation: Benosman, M.A.; Atinc, G.M., "Nonlinear Adaptive Control for Electromagnetic Actuators", *SIAM Conference on Control and its Applications*, dx.doi.org/10.1137/1.9781611973273.5, ISBN: 978-1-61197-327-3, July 2013

Contacts: Mouhacine Benosman

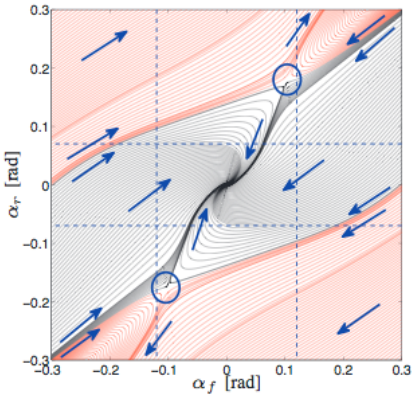


We study here the problem of robust 'soft-landing' control for electromagnetic actuators. Soft landing requires accurate control of the actuator's moving element between two desired positions. We present here two nonlinear adaptive controllers to solve the problem of robust trajectory tracking for the moving element. The first controller is based on classical nonlinear adaptive technique. Second, we present a controller based on the so-called Input-to-State Stability (ISS), merged with gradient descent estimation filters to estimate the uncertain parameters. We demonstrate the effectiveness of these controllers on a simulation example.

Vehicle Yaw Stability Control by Coordinated Active Front Steering and Differential Braking in the Tire Sideslip Angles Domain

Citation: Di Cairano, S.; Tseng, H.E.; Bernardini, D.; Bemporad, A., "Vehicle Yaw Stability Control by Coordinated Active Front Steering and Differential Braking in the Tire Sideslip Angles Domain", *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/ TCST.2012. 2198886, ISSN: 1063-6536, Vol. 21, Issue 4, pp. 1236-1248, July 2013

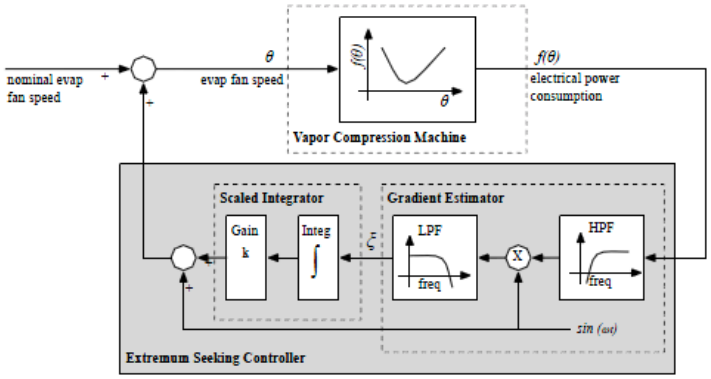
Contacts: Stefano Di Cairano



Vehicle active safety receives an always increasing attention in the attempt to achieve zero accidents on the road. In this paper we investigate a control architecture that has the potential of improving yaw stability control by achieving faster convergence and reduced impact on longitudinal dynamics. We consider a system where active front steering and differential braking are available and we propose a Model Predictive Control (MPC) strategy to coordinate the actuators. We formulate the vehicle dynamics with respect to the tire slip angles and we use a piecewise affine approximation of the tire force characteristics. The resulting piecewise affine system is used as prediction model in a hybrid MPC strategy. After assessing the benefits of the proposed approach, we synthesize the controller by using a switched model predictive control strategy.

Extremum Seeking Control for Energy Optimization of Vapor Compression Systems

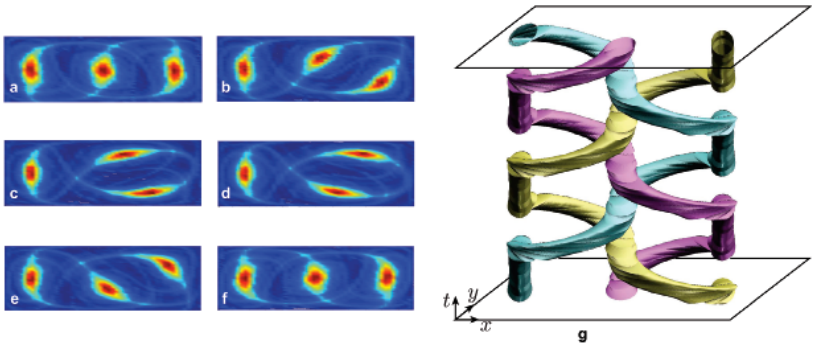
Citation: Burns, D.J.; Laughman, C.R., "Extremum Seeking Control for Energy Optimization of Vapor Compression Systems", International Refrigeration and air Conditioning Conference at Purdue, ID: 2192, July 2012
Contacts: Daniel J. Burns, Christopher R. Laughman



An energy optimizing extremum seeking controller is developed for vapor compression systems (VCS) that automatically discovers sets of inputs that minimizes the energy consumption while the machine is in operation. This controller optimizes an input-output map (from VCS inputs to electrical energy consumed) in realtime, and without relying on a model of the dynamics of a vapor compression system. Experiments on an inverter-driven room air conditioner demonstrated convergence of inputs to their optimal values, resulting in an improvement in COP of 10-20% for some operating points.

Topological Chaos, Braiding and Bifurcation of Almost-cyclic Sets

Citation: Grover, P.; Ross, S.; Stremier, M.; Kumar, P., "Topological Chaos, Braiding and Bifurcation of Almost-cyclic Sets", AIP Choas, Vol. 22, Issue 4, December 2012
Contacts: Piyush Grover

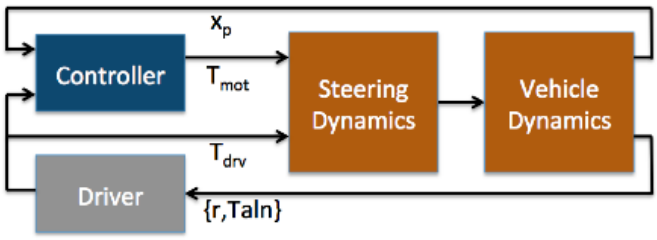


In certain two-dimensional time-dependent flows, the braiding of periodic orbits provides a way to analyze chaos in the system through application of the Thurston-Nielsen classification theorem (TNCT). We expand upon earlier work that introduced the application of the TNCT to braiding of almost-cyclic sets, which are individual components of almost-invariant sets. We discuss the bifurcation of the almost-cyclic sets as a system parameter is varied, which results in a sequence of topologically distinct braids. We show that, for Stokes' flow in a lid-driven cavity, these various braids give good lower bounds on the topological entropy over the respective parameter regimes in which they exist. We make the case that a topological analysis based on spatiotemporal braiding of almost-cyclic sets can be used for analyzing chaos in fluid flows.

Vehicle Yaw Dynamics Control by Torque-based Assist Systems Enforcing Driver's Steering Feel Constraints

Citation: Zafeiropoulos, S.; Di Cairano, S., "Vehicle Yaw Dynamics Control by Torque-based Assist Systems Enforcing Driver's Steering Feel Constraints", *American Control Conference (ACC)*, ISBN: 978-1-4799-017707, ISSN: 0743-1619, pp. 6746-6751, June 2013

Contacts: Stefano Di Cairano



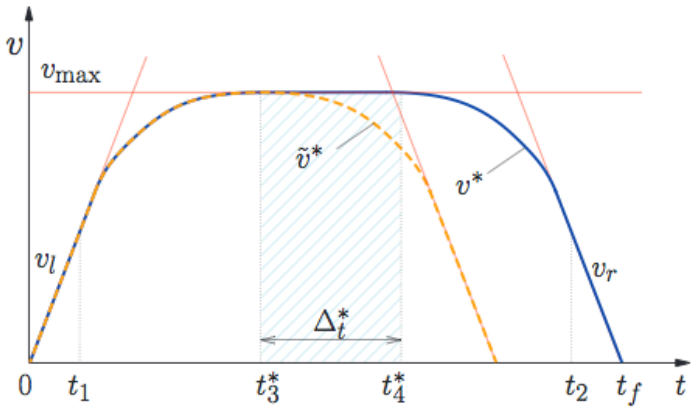
We investigate the control of torque-based steering assist systems for improving yaw rate tracking and vehicle stabilization. As opposed to active front steering systems based on harmonic motors, torque-based steering assist systems are mechanically coupled with the driver. Thus, besides standard vehicle and actuators constraints, specific constraints related to the driver-actuator interaction need to be enforced. These constraints can be formulated to achieve a multiplicity of goals, including avoiding excessive strain in the driver's arms, and preserving the driver's "feel for the road". In order to achieve high control performance and constraints satisfaction, we implement controllers based on linear and switched model predictive control, where different types of driver's steering feel constraints are enforced. The different controllers are evaluated in simulation maneuvers to analyze their capabilities and the impact of the constraints in terms of vehicle cornering, stabilization, and driver's steering feel.

Real-Time Energy-Optimal Trajectory Generation for a Servo Motor

Citation: Zhao, Y.; Wang, Y.; Bortoff, S.A.; Ueda, K., "Real-Time Energy-Optimal Trajectory Generation for a Servo Motor", *American Control Conference (ACC)*, ISBN: 978-1-4799-0177-7, ISSN: 0743-1619, pp. 1165-1170, June 2013

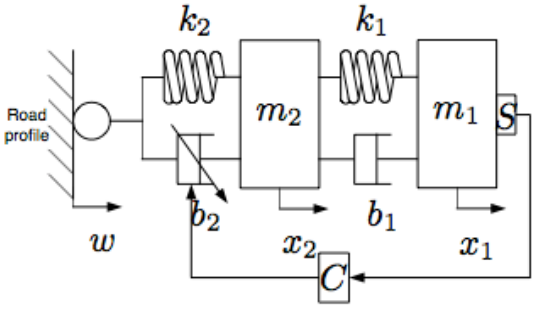
Contacts: Yebin Wang, Scott Bortoff

This paper considers the fast generation of speed and acceleration constrained energy-optimal trajectories for a motor system performing a point-to-point positioning task with a fixed final time. An algorithm is proposed to obtain the energy-optimal solution by solving a series of Two-point Boundary Value Problems (TBVPs) with guaranteed convergence. The algorithm is capable of generating energy-optimal trajectories in real-time.



Sub-optimal Control Design of a Semi-active Vibration Reduction System

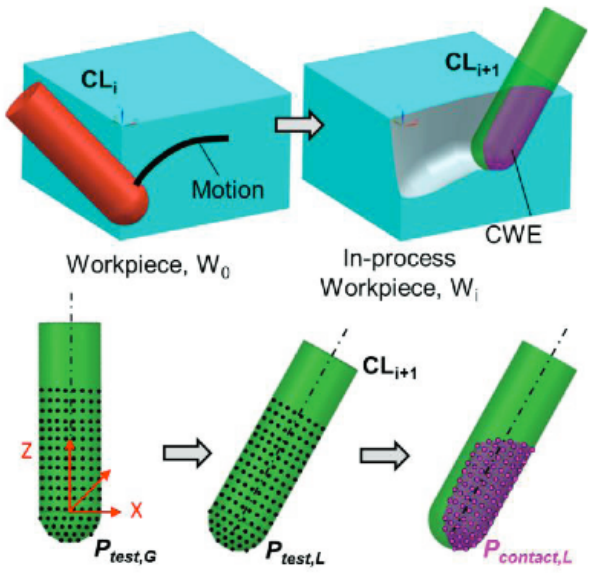
Citation: Wang, Y.; Utsunomiya, K., "Sub-optimal Control Design of a Semi-active Vibration Reduction System", *American Control Conference (ACC)*, ISBN: 978-1-4799-0177-7, ISSN: 0743-1619, pp. 4110-4115, June 2013
Contacts: Yebin Wang



This paper considers the vibration reduction of transportation systems using semi-active actuators to improve the ride quality. Control design for the resultant semi-active system is difficult for nonlinear dynamics, constrained control, lack of performance-oriented nonlinear control design, and limited state information. A sub-optimal control structure is proposed to address the performance requirement by mimicking the optimal control. A specific sub-optimal control is provided and implemented with one measurement to reduce the hardware cost. Performance analysis of the sub-optimal control is investigated. The semi-active system with the suboptimal control is simulated to demonstrate the effectiveness.

Cutter Workpiece Engagement Calculations for Five-axis Milling using Composite Adaptively Sampled Distance Fields

Citation: Erdim, H.; Sullivan, A., "Cutter Workpiece Engagement Calculations for Five-axis Milling using Composite Adaptively Sampled Distance Fields", *CIRP Conference on Modeling of Machining Operations (CIRP CMMO)*, dx.doi.org/10.1016/j.procir.2013.06.130, Vol. 8, pp. 438-443, June 2013
Contacts: Alan Sullivan



Composite adaptively sampled distance fields are a new approach to shape representation that is well suited for Numerically Controlled (NC) milling simulation. In NC milling, as the milling tool moves along the tool path, it carves out a swept volume and a portion of the work piece is removed. During the milling tool motion, it is in contact with the work piece over an instantaneous common surface, which is called the Cutter Workpiece Engagement (CWE) surface. In order to model the process mechanics and dynamics accurately, it is important to have a precise geometric representation of the CWE surface. We provide a brief introduction to distance fields for swept volumes and describe a new method for determining the CWE surface for general and complex five-axis NC milling.

Algorithms

Researchers in the Algorithms group at MERL develop solution methods for optimization problems involving very large numbers of variables. Typically these arise in inference problems involving images, video, or audio; network transport problems; coding and compression problems; or design problems. Usually these problems are characterized by very complicated probability distributions in extremely high dimensional spaces. Because classical approaches to these problems are infeasible, our results can open new business opportunities where there are no competitive technologies. Another main research theme involves adaptively-sampled distance fields (ADFs), a new representation for shapes of any dimension. ADFs have distinct advantages over previous forms, including superior font and graphical rendering for digital displays.

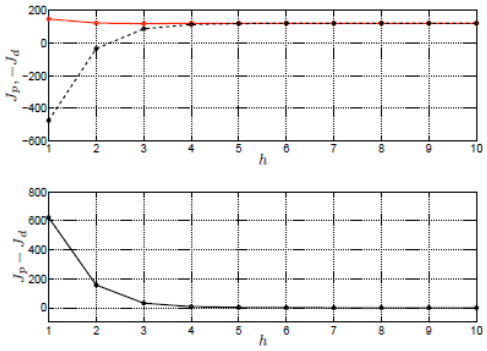
Most of the group's work revolves around graph-based optimizations and inference, where the graph is a representation of the problem constraints and a probability distribution over possible solutions. Through formal analysis we identify tractable estimation or approximation schemes. This meshes with MERL's expertise in fields and technologies such as belief propagation, machine learning, computer vision, dynamic programming, convex optimization, coding and communications theory, and signal processing.

Recent Research

Projection-free Parallel Quadratic Programming for Linear Model Predictive Control

Citation: Di Cairano, S.; Brand. M.E.; Bortoff, S.A., "Projection-free Parallel Quadratic Programming for Linear Model predictive Control", *International Journal of Control*, DOI: 10.1080/00207179.2013.801080, Vol. 86, Issue 8, pp. 1367-1385, July 2013

Contacts: Stefano Di Cairano, Matthew Brand, Scott Bortoff



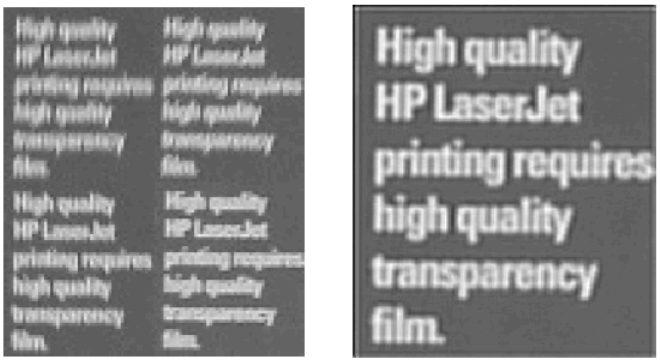
A key component in enabling the application of model predictive control (MPC) in fields such as automotive, aerospace and factory automation is the availability of low-complexity fast optimization algorithms to solve the MPC finite horizon optimal control problem in architectures with reduced computational capabilities. In this paper we introduce a projection-free iterative optimization algorithm and discuss its application to linear MPC.
The algorithm, originally developed by Brand for non-negative quadratic programs, is based on a multiplicative update rule and it is shown to converge to a fixed point which is the optimum. An acceleration technique based on a projection-free line search is also introduced, to speed-up the convergence to the optimum. The algorithm is applied to MPC through the dual of the quadratic program (QP) formulated from the MPC finite time optimal control problem. We discuss how termination conditions with guaranteed degree of suboptimality can be enforced, and how the algorithm performance can be optimized by pre-computing the matrices in a parametric form. We show computational results of the algorithm in three common case studies and we compare such results with the results obtained by other available free and commercial QP solvers.

Parallel Quadratic Programming for Image Processing

Citation: Brand, M.; Chen, D., "Parallel Quadratic Programming for Image Processing", *IEEE International Conference on Image Processing (ICIP)*, DOI: 10.1109/ICIP.2011.6116089, pp. 2261-2264, September 2011

Contacts: Matthew E. Brand

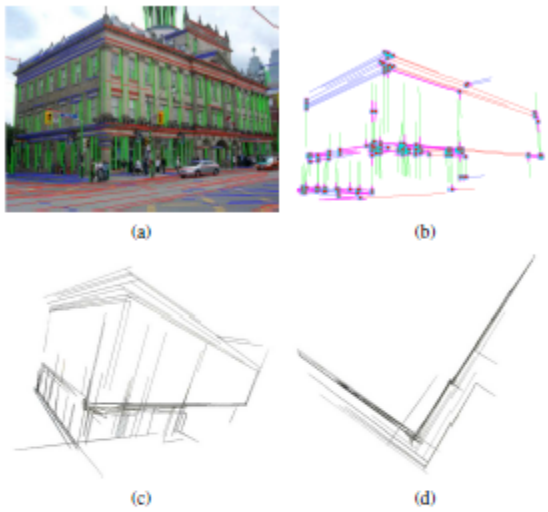
Many image processing and computer vision problems can be solved as quadratic programs in the non-negative cone. This paper develops a provably convergent multiplicative update that has a simple form and is amenable to fine-grained data parallelism. Classic algorithms for deblurring, matrix factorization, and tomography are recovered as special cases. This paper also demonstrates applications to super-resolution, labeling and segmentation.



(a) 4 of 30 low-res images (b) reconstructed high-res image

Lifting 3D Manhattan Lines from a Single Image

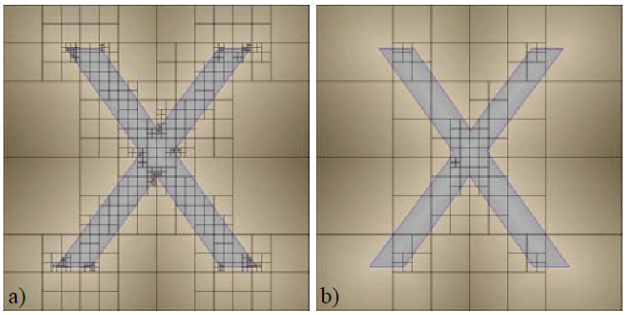
Citation: Ramalingam, S.; Brand. M.E., "Lifting 3D Manhattan Lines from a Single Image", *IEEE International Conference on Computer Vision (ICCV)*, DOI: 10.1109/ICCV.2013.67, ISSN: 1550-5499, pp. 497-504, December 2013
Contacts: Srikumar Ramalingam, Matthew Brand



We propose a novel and an efficient method for reconstructing the 3D arrangement of lines extracted from a single image, using vanishing points, orthogonal structure, and an optimization procedure that considers all plausible connectivity constraints between lines. Line detection identifies a large number of salient lines that intersect or nearly intersect in an image, but relatively few of these apparent junctions correspond to real intersections in the 3D scene. We use linear programming (LP) to identify a minimal set of least-violated connectivity constraints that are sufficient to unambiguously reconstruct the 3D lines. In contrast to prior solutions that primarily focused on well-behaved synthetic line drawings with severely restricting assumptions, we develop an algorithm that can work on real images.

Designing with Distance Fields

Citation: Frisken, S.F.; Perry, R.N**.,** "Designing with Distance Fields**"**, *ACM SIGGRAPH*, ISBN: 1-59593-364-6, pp. 60-66, July 2006
Contacts: Ronald Perry



Distance fields provide an implicit representation of shape that has advantages in many application areas; in this overview, we focus on their use in digital design. Distance fields have been used in Computer Aided Design since the 1970's (e.g. for computing offset surfaces and for generating rounds and filets). Modern computer systems coupled with efficient representations and methods for processing distance fields have made it possible to use distance fields in interactive design systems. This overview reviews previous work in distance fields, discusses the properties and advantages of distance fields that make them suitable for digital design, and describes Adaptively Sampled Distance Fields (ADFs), a distance field representation capable of representing detailed, high quality, and expressive shapes. ADFs are both efficient to process and have a relatively small memory footprint.

Stochastic Shortest Paths via Quasi-convex Maximization

Citation: Nikolova, E.; Kelner, J.; Brand, M.; Mitzenmacher, M., "Stochastic Shortest Paths Via Quasi-convex Maximization", *European Symposium on Algorithms (ESA)*, ISBN:3-540-38875-3, pp. 552 - 563, September 2006

Contacts: Matthew Brand

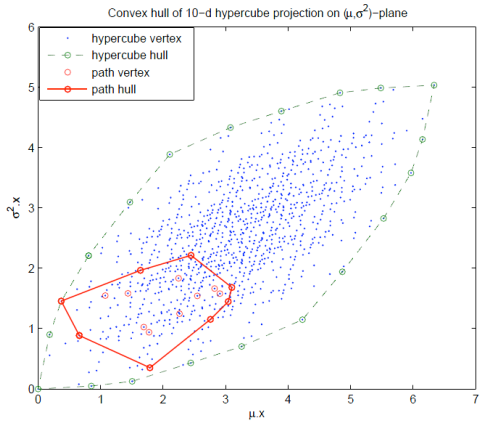


Fig. 1. Projection of the unit hypercube (representing all edge subsets) and the path polytope onto the (μ, σ^2)-plane.

We consider the problem of finding shortest paths in a graph with independent randomly distributed edge lengths. Our goal is to maximize the probability that the path length does not exceed a given threshold value (deadline). We give a surprising exact $n^{\theta(\log n)}$ algorithm for the case of normally distributed edge lengths, which is based on quasi-convex maximization. We then prove average and smoothed polynomial bounds for this algorithm, which also translate to average and smoothed bounds for the parametric shortest path problem, and extend to a more general non-convex optimization setting. We also consider a number other edge length distributions, giving a range of exact and approximation schemes.