MITSUBISHI ELECTRIC RESEARCH LABORATORIES
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MERL Annual Report 2015

Waters, R.C.

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Abstract

Annual Report

April 2014 through March 2015

TR2015-000

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.

Mitsubishi Electric Research Laboratories

Mitsubishi Electric Research Laboratories, Inc.
201 Broadway, Cambridge, Massachusetts 02139

Mitsubishi Electric Research Laboratories (MERL)

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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:

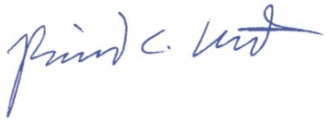
- Hiring very high quality researchers and supporting them strongly with a flexible work environment featuring teamwork both inside MERL and with our colleagues at Mitsubishi Electric.
- Participating in the world research community, publishing our work while maintaining the confidentiality of business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

- Dr. Richard C. (Dick) Waters (President & CEO)
  - Dr. Takuji Magara (EVP & CFO)
  - Dr. Jinyun Zhang, IEEE Fellow (VP & Director)
    - EC: Electronics & Communications Group - Dr. Phil Orlik
    - MM: Multimedia Group - Dr. Anthony Vetro, IEEE Fellow
    - DA: Data Analytics Group - Dr. Daniel Nikovski
  - Dr. Joseph Katz, IEEE & OSA Fellow (VP & Director)
    - SA: Spatial Analysis Group - Dr. Jay Thornton
    - ME: Mechatronics Group - Dr. Scott Bortoff
    - AL: Algorithm Group - Dr. Joseph Katz, IEEE & OSA Fellow
  - Dr. Anthony Vetro, IEEE Fellow (Deputy Director, IP)

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.

Takuji Magara *Ph.D., Tokyo Institute of Technology, 1992*
Executive Vice President & CFO

Takuji Magara joined Mitsubishi Electric's Nagoya Works in 1982 where he developed Electric Discharge Machine (EDM) systems, eventually becoming the Senior Manager of EDM Systems Department. In 2008, he then moved to the Advanced Technology Research Center (ATC) as Senior Manager of the Laser and Electric Machining Department. He rose to General Manager of the Electro-Mechanical Technology Laboratory at ATC, before coming to MERL in 2015.

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 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

Anthony 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.

Mitsubishi Electric

One of the world's largest companies, Mitsubishi Electric Corporation has $36 billion in annual sales, $2.6 billion in operating profits (in the year ending in March 2015) and more than 130,000 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. Keisuke Kojima - Fellow, Optical Society of America
Dr. Huifang Sun - Fellow, Institute of Electrical and Electronic Engineer
Dr. Anthony Vetro - Fellow, Institute of Electrical and Electronic Engineers
Dr. Jin Zhang - Fellow, Institute of Electrical and Electronic Engineers

Awards and Major Events

A team from MERL and Mitsubishi Electric in Japan received a 2014 R&D 100 award for its work on Mitsubishi Electric's MELFA-3D Vision system for industrial robot arms. This system completely automates bin picking — picking up parts that are randomly placed in a bin and aligning their poses for assembly processes.

Duong, T.Q., Duy, T.T., Kim, K.J., Bao, V.N.Q., Elkashlan, M., **"**Interference Investigation for Cognitive Spectrum Sharing Networks with Reactive DF Relay Selection**"**, International Conference on Communications and Networking in China (CHINACOM), August 2014, received a best paper award from the conference.

Dr. Anthony Vetro is the 2015 recipient of the InterNational Committee for Information Technology Standards (INCITS) Gene Milligan Award for Effective Committee Management.

It is also worthy of note that MERL had a large number of papers in some of the most selective and prestigious conferences related to MERL's areas of research: 9 in the IEEE International Conference on Acoustics, Speech & Signal Processing (ICASSP), 10 in the American Control Conference (ACC), 5 in the IEEE PES Conference on Innovative Smart Grid Technologies (ISGT), and 6 in the Optical Fiber Communication (OFC) Conference. 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.

Valeria Arlunno *Ph.D., Technical University of Denmark (DTU), 2013*
Visiting Member Research Staff

Valeria's interests are in applications of digital signal processing for coherent optical communications. She is particularly interested in advanced modulation formats, equalization schemes and demodulation-decoding cooperation. Her PhD focused on advance equalization techniques for digital coherent optical receivers.

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 Manager 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*
Senior 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.

Karl Berntorp *Ph.D., Lund University, 2014*
Visiting Member Research Staff

Karl's doctoral research addressed development of particle-filtering methods, and sensor fusion and optimal control applied to vehicles and robots. His research interests are in nonlinear estimation and control, path planning, motion control, and their applications to automotive, robotics, and aerospace systems.

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*
Senior 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

Matt 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.

Kiran Byadarhaly *Ph.D., University of Cincinnati, 2013*
Visiting Member Research Staff

Prior to joining MERL, Kiran was a part of the Complex Adaptive Systems Laboratory at the University of Cincinnati where he worked on building computational and mathematical models for cognitive systems focusing on movement control. His interests include statistical machine learning, data mining, neural modeling & computational neuroscience and optimization.

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.

Claus Danielson *Ph.D., University of California, Berkeley, 2008*
Member Research Staff

Claus' research interests are in model predictive control, constrained control, and networked control systems. His doctoral research was focused on exploiting symmetry in large-scale control and optimization problems.

Stefano Di Cairano *Ph.D., University of Siena, 2008*
Senior Principal Member Research Staff,
Optimization-Based Control 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.

Hakan Erdogan *Ph.D., University of Michigan, 1999*
Visiting Member Research Staff,

Hakan is a faculty member at Sabanci University in Istanbul, Turkey. He is currently a visiting researcher at Mitsubishi Electric Research Laboratories, Cambridge MA during his sabbatical for the 2014-2015 academic year. He was with the Human Language Technologies group at IBM T.J. Watson Research Center, NY between 1999 and 2002 where he focused on the following speech recognition problems: acoustic modeling, language modeling, and speech translation.

Amir-massoud Farahmand *Ph.D., University of Alberta, 2011*
Member Research Staff

Amir-massoud's research interests are in reinforcement learning, sequential decision-making under uncertainty, and nonparametric methods in machine learning and statistics. His focus at MERL is on developing theoretically-sound algorithms for challenging industrial problems. Before joining MERL in December 2014, he held postdoctoral fellowships at Carnegie Mellon University and McGill University.

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*
Principal 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.

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.

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.

Ulugbek Kamilov *Ph.D., Ecole Polytechnique Federale de Lausanne, 2015*
Member Research Staff

Ulugbek's PhD research developed statistical estimation techniques for solving inverse problems in biomicroscopy. His interests include signal acquisition and processing, signal representations and resolution of inverse problems. Prior to joining to MERL, Ulugbek was an exchange student at Carnegie Mellon University in 2007, a visiting student at MIT in 2010, and a visiting student researcher at Stanford University.

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*
Senior 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.

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.

Gim Hee Lee *Ph.D., ETH Zurich, 2014*
Visiting Member Research Staff

Prior to his PhD, Gim Hee worked as a member of technical staff at DSO National Laboratories, Singapore. His main area of research is computer vision for robotics perception. During his PhD, he worked on the European Commission funded sFly and V-Charge projects, where the objective was to build autonomous Micro-Aerial Vehicles (MAVs) and self-driving cars with cameras as the main sensor.

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*
Principal 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,*
Principal 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.

Alexander Malyshev, *Ph.D., USSR Academy of Sciences, Novosibirsk, 1984*
Visiting Member Research Staff

During his 30 years in the academy, Alexander contributed to the theory of partial differential equations, numerical simulation in continuum mechanics, applied linear algebra, parallel numerical algorithms, and image processing. His focus at MERL is on efficient algorithms for model predictive control, image and signal processing and data analysis.

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 S. Millar *Ph.D., University College London (UCL), 2011*
Principal 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.

Francis Morales *B.S., Universidad APEC, 2007*
Systems & Network Administrator

Francis has been in the IT field since 2001 with experience in different IT industries with special interest in OSs, Networking and Security. Prior to joining MERL he worked 4 years in the healthcare IT field. Previous to that, he was the principal of a small Computer Service business in his home country.

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*
Electronics & Communications Group Manager

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.

Milutin Pajovic *Ph.D., Massachusetts Institute of Technology, 2014*
Member Research Staff

Milutin's doctoral thesis studied adaptive signal processing with deficient sample support using random matrix theory methods and considered adaptive sensor array processing, channel estimation and channel equalization as specific applications. His interests also include communications, statistical signal processing and machine learning.

Kieran Parsons *Ph.D., University of Bristol, UK, 1996*
Senior Principal Member Research Staff, Optical Team Leader

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.

Hongtao Qiao *Ph.D., University of Maryland, 2014*
Visiting Member Research Staff

Prior to his PhD, Hongtao worked at Carrier Corporation developing advanced steady-state computer simulations for HVAC systems. During his PhD, he developed a comprehensive transient modeling framework for thermo-fluid systems to explore complex dynamic characteristics of vapor compression cycles. Currently, Hongtao works on the control-oriented multi-physical system modeling.

Arvind U. Raghunathan *Ph.D., Carnegie Mellon University, 2004*
Senior 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*
Senior 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.

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*
Visiting 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

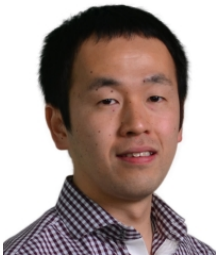
First at U.C. Berkeley, then at Lawrence Livermore National Laboratory, Alan studied interactions between ultra-high intensity femtosecond lasers and plasmas. Prior to joining MERL in 2007, he worked at a series of start-ups where he developed a novel volumetric 3D display technology. At MERL His research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

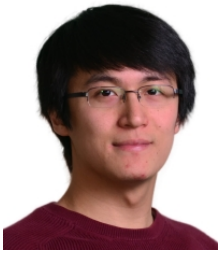
Jeroen came to MERL in 1997 as intern, and was subsequently hired as research associate. He temporarily left MERL to pursue a Ph.D. and returned early 2013. At MERL he has made contributions in the areas of computer graphics, computer vision and computational photography. His interests include 3D reconstruction,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

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.

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.

Shao, J.; Ma, R.; Teo, K.H.; Shinjo, S.; Yamanaka, K., **"A Fully Analog Two-way Sequential GaN Power Amplifier with 40% Fractional Bandwidth"**, *IEEE MTT-S International Wireless Symposium (IWS)*, WE-1-E1 0820-0840 (203), March 2015 (TR2015-021)

Koike-Akino, T.; Millar, D.S.; Kojima, K.; Parsons, K., **"Coded Modulation Design for Finite-Iteration Decoding and High-Dimensional Modulation"**, *Optical Fiber Communication Conference (OFC)*, DOI: 10.1364/OFC.2015.W4K.1, ISBN: 978-1-55752-937-4, March 2015 (TR2015-016)

Kojima, K.; Horiguchi, Y.; Koike-Akino, T.; Shimakura, Y.; Enoki, K.; Yagyu, E., **"Separation of Semiconductor Laser Intrinsic Linewidth and 1/f Noise Using Multiple Fiber Length for Self-heterodyne Method"**, *Optical Fiber Communication Conference (OFC)*, DOI: 10.1364/OFC.2015.W2A.18, ISBN: 978-1-55752-937-4, March 2015 (TR2015-017)

Maher, R.; Lavery, D.; Millar, D.S.; Alvarado, A.; Parsons, K.; Bayvel, P., **"Reach Enhancement of 100% for a DP-64QAM Super Channel using MC-DBP with an ISD of 9b/s/Hz"**, *Optical Fiber Communication Conference (OFC)*, DOI: 10.1364/OFC.2015.Th4D.5, ISBN: 978-1-55752-937-4, March 2015 (TR2015-015)

Kojima, K.; Koike-Akino, T.; Millar, D.S.; Parsons, K., **"Design of Constant Modulus Modulation Considering Envelopes"**, *Optical Fiber Communication Conference (OFC)*, DOI: 10.1364/OFC.2015.24K.5, ISBN: 978-1-55752-937-4, March 2015 (TR2015-020)

Millar, D.S.; Maher, R.; Lavery, D.; Koike-Akino, T.; Alvarado, A.; Paskov, M.; Kojima, K.; Parsons, K.; Li, R.; Savory, S.J.; Bayvel, P., **"Transceiver-Limited High Spectral Efficiency Nyquist-WDM Systems"**, *Optical Fiber Communication Conference (OFC)*, DOI: 10.1364/OFC.2015.Th2A.13, ISBN: 978-1-55752-937-4, March 2015 (TR2015-018)

Xia, T.; Koike-Akino, T.; Millar, D.S.; Kojima, K.; Parsons, K.; Miyata, Y.; Sugihara, K.; Matsumoto, W., **"Dynamic Window Decoding for LDPC Convolutional Codes in Low-Latency Optical Communications"**, *Optical Fiber Communication Conference (OFC)*, DOI: 10.13464/OFC.2015.Th3E.A, ISBN: 978-1-55752-937-4, March 2015 (TR2015-019)

Gerkmann, T.; Krawczyk, M.; Le Roux, J., **"Phase Processing for Single-Channel Speech Enhancement: History and Recent Advances"**, *IEEE Signal Processing Magazine*, DOI: 10.1109/MSP.2014.2369251, ISSN: 1053-5888, vol. 32, pp. 55-66, March 2015 (TR2014-122)

Benosman, M., **"Extremum Seeking-based Indirect Adaptive Control and Feedback Gains Auto-Tuning for Nonlinear Systems"**, Chapter 8 in Control Theory: Perspectives, Applications and Developments, Francisco Miranda ed., Nova Science Publishers, ISBN: 978-1-63482-707-2, February 2015 (TR2015-009)

Long, J.; Wang, B., **"A Metamaterial-Inspired Sensor for Combined Inductive-Capacitive Detection"**, *Applied Physics Letters*, DOI: dx.doi.org/10.a063/1.4913228, vol. 106, February 2015 (TR2015-014)

Tan, Z.; Sun, H.; Nikovski, D.N.; Takano, T.; Kojima, Y.; Ohno T., **"A Generalized Admittance Based Method for Fault Location Analysis of Distribution Systems"**, *IEEE PES Conference on Innovative Smart Grid Technologies*, ISGT2015-000176, February 2015 (TR2015-013)

Dubey, A.; Sun, H.; Nikovski, D.N.; Takano, T.; Kojima, Y.; Ohno, T., **"Locating Double-line-to-ground Faults using Hybrid Current Profile Approach"**, *IEEE PES Conference on Innovative Smart Grid Technologies (ISGT)*, ISGT2015-000094, February 2015 (TR2015-003)

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Di Cairano, S.; Kolmanovsky, I.V., **"Coordinating Controllers for Constrained Linear Systems by Virtual State Governors"**, *IEEE Transactions on Automatic Control*, DOI: 10.2209/TAC.2014.2386919, ISSN: 0018-9286, vol. PP, pp. 1, December 2014 (TR2015-011)

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Wang, Y.; Ishwar, P.; Rane, S., **"An Elementary Completeness Proof for Secure Two-party Computation Primitives"**, *IEEE Information Theory Workshop (ITW)*, DOI: 10.1109/ITW.2014.6970886, ISSN: 1662-9019, pp. 521-525, November 2014 (TR2014-092)

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Deng, Y.; Wang, Y.; Teo, K.H.; Harley, R.G., **"Space Vector Modulation Method for Modular Multilevel Converters"**, *Conference of the IEEE Industrial Electronics Society (IECON)*, DOI: 10.1109/IECON>2014.7049213, pp. 4715-4721, October 2014 (TR2014-102)

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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, model predictive control, nonlinear dynamical systems, system-level dynamic modeling & analysis, mechatronic co-design, thermo-fluid system dynamics, and applications to factory automation, elevators, space systems, automotive mechatronics, and HVAC.

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

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

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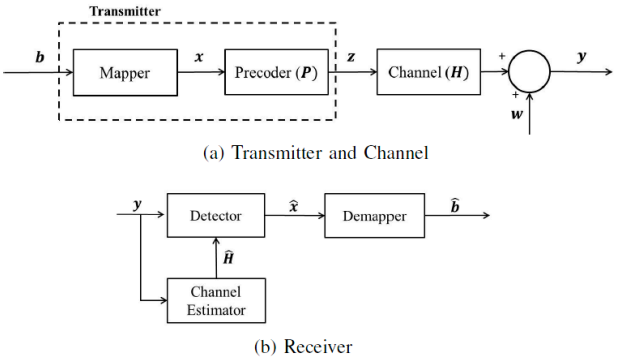

Fig. 1: Block diagram of the considered system.

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.

Han-Kobayashi and Dirty-Paper Coding for Superchannel Optical Communications

Citation: Koike-Akino, T., Kojima, K., Millar, D.S., Parsons, K., Kametani, S., Sugihara, T., Yoshida, T., Ishida, K., Miyata, Y., Matsumoto, W., Mizuochi, T., "Han-Kobayashi and Dirty-Paper Coding for Superchannel Optical Communications", *Journal of Lightwave Technology*, DOI: 10.1109/JLT.2015.2397435, ISSN: 0733-8724, Vol. 33, No. 7, pp. 1292-1299, February 2015.

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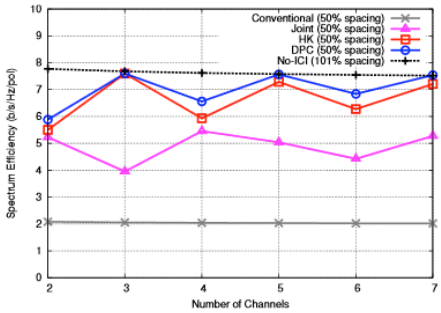

Fig. 10. Spectrum efficiency vs. number of channels N ($\delta f = 0.50$).

Superchannel transmission is a candidate to realize Tb/s-class high-speed optical communications. In order to achieve higher spectrum efficiency, the channel spacing shall be as narrow as possible. However, densely allocated channels can cause nonnegligible inter-channel interference (ICI) especially when the channel spacing is close to or below the Nyquist bandwidth. In this paper, we consider joint decoding to cancel the ICI in dense superchannel transmission. To further improve the spectrum efficiency, we propose the use of Han-Kobayashi (HK) superposition coding. In addition, for the case when neighboring subchannel transmitters can share data, we introduce dirty-paper coding (DPC) for pre-cancellation of the ICI.

Stability Metric Based Routing Protocol for Low-Power and Lossy Networks

Citation: Yang, X., Guo, J., Orlik, P.V., Parsons, K., Ishibashi, K., "Stability Metric Based Routing Protocol for Low-power and Lossy Networks", *IEEE International Conference on Communications (ICC)*, DOI: 10.1109/ICC.2014.6883895, June 2014, pp. 3688-3693.

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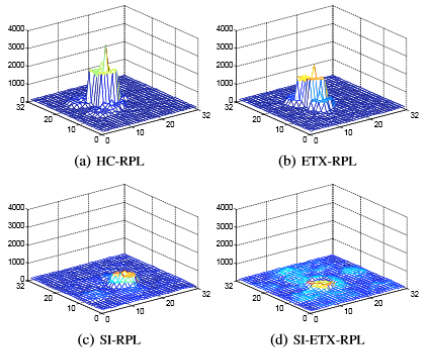


Fig. 4: The 3D meshes indicate the number of control messages transmitted by every node.

To design a routing protocol for applications over low-power and lossy networks (LLNs), the IETF ROLL Working Group standardized the IPv6 Routing Protocol for LLNs (RPL), which organizes nodes in a LLN into a tree-like topology called Destination Oriented Directed Acyclic Graph (DODAG). RPL shows good scalability and fast network setup. However, it may suffer from severe unreliability due to the selection of suboptimal routes with low quality links. To optimize the reliability of RPL routes, this paper proposes a stability metric based routing protocol named sRPL for reliable routing and data collection in LLNs. We introduce a new routing metric for RPL called stability index (SI), which exploits stability characteristics of RPL nodes to select more stable routes. In addition, we present a passive and lightweight network layer technique to measure the bi-directional expected transmission count (ETX) for wireless links in LLNs. As a use case of SI, we combine SI metric with ETX metric to make routing decisions. Simulation results show that sRPL can improve packet delivery rate of RPL routing protocol by 20%.

Constant Modulus 4D Optimized Constellation Alternative for DP-8QAM

Citation: Kojima, K., Millar, D.S., Koike-Akino, T., Parsons, K., "Constant Modulus 4D Optimized Constellation Alternative for DP-8QAM", *European Conference on Optical Communication (ECOC), DOI: 10.1109/ECOC.2014.6964188, Septem*ber 2014, pp. 1-3.

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

We propose a constant modulus 4D format as an alternative to DP-8QAM. It has 0.4dB lower SNR at BER = 10^-2, and 1 dB higher span loss budget in nonlinear regime.

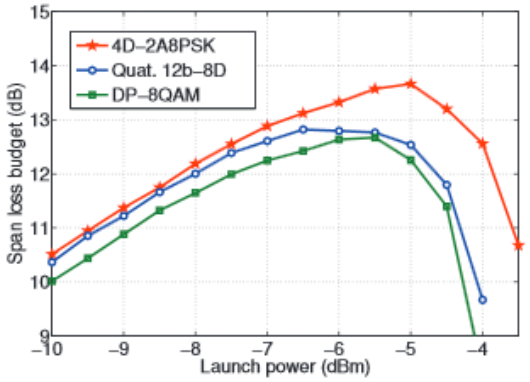


Fig. 7: Span loss budget vs launch power for 4D-2A8PSK, Quaternary 12b-8D, and DP-8QAM codes for 75spans of 80km NZDSF at a target BER = 10^{-2}.

Outphasing Multi-Level RF PWM for Inter-Band Carrier Aggregation in Digital Transmitters

Citation: Chung, S., Ma, R., Teo, K.H., Parsons, K., "Outphasing Multi-Level RF PWM Signals for Inter-Band Carrier Aggregation in Digital Transmitters", *IEEE Radio Wireless Week (RWW),* January 2015.
Contacts: Rui Ma, Koon Hoo Teo, Kieran Parsons

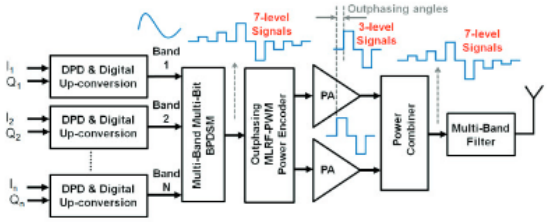


Fig. 2. Proposed outphasing multi-level RF-PWM (MLRF-PWM) transmitter architecture for inter-band CA.

A novel non-contiguous concurrent multiband digital-RF transmitter architecture is presented, which is based on outphasing the multi-level RF pulse-width modulated signals (MLRF-PWM) for digital Class-S power amplifiers. In order to improve the transmitter power efficiency, the outphasing modulation in the proposed architecture effectively increases the number of MLRF-PWM signal output levels. In addition, a multi-band multibit band-pass delta-sigma modulator (BPDSM) with a hard clipping technique is introduced, which further improves power coding efficiency by trading off distortion performance with coding efficiency. Experimental results with a dual-channel 25-GSPS arbitrary waveform generator (AWG) demonstrate non-contiguous carrier aggregation for 3-level Class-S PAs with inter-band LTE signals at 874 MHz and 1501 MHz for the channel bandwidth of 10-MHz and 20-MHz, respectively. The proposed outphasing MLRF-PWM technique achieves 59.5% power coding efficiency, which is significant improvement from the 8.6% coding efficiency of conventional 3-level BPDSM with the experimental dual band LTE signal transmission.

Classification of Wireless Interference on 2.4GHz Spectrum

Citation: Weng, Z., Orlik, P.V., Kim, K.J., "Classification of Wireless Interference on 2.4GHz Spectrum", *IEEE Wireless Communications and Networking Conference (WCNC)*, DOI: 10.1109/WCNC.2014.6952168, April 2014, pp. 786-791.
Contacts: Philip V. Orlik, Kyeong Jin Kim

We propose two methods for the detection of RF interference. The first one is for the detection of the interferences from microwave ovens, and the second one is for Wi-Fi and Bluetooth signals. The motivation of this work is to design a system for reliable wireless communication. Specifically, the systems equipped with interference detectors will be able to choose the appropriate time intervals to transmit signals in the presence of other interferences, therefore avoiding unnecessary collisions and retransmissions.

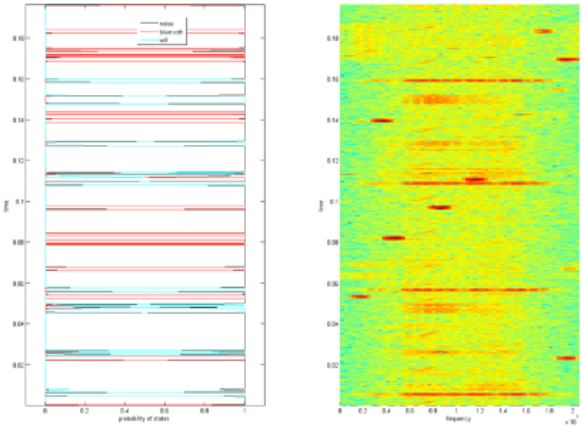


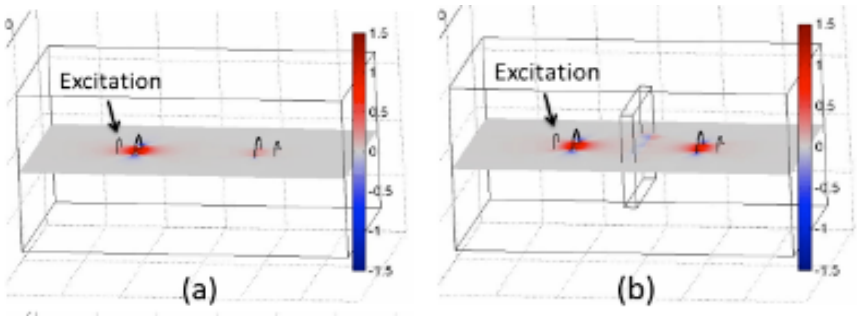
Fig. 10. The result of the classification.

Metamaterials and Resonant Array Wireless Power Systems

Citation: Yerazunis, W.S., Wang, B., Teo, K.H., "Metamaterials and Resonant Array Wireless Power Systems", *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, DOI: 10.1109/APS.2014.6905027, ISSN: 1522-3965, ISBN: 978-1-4799-3538-3, July 2014, pp. 1403-1404.

Contacts: William S. Yerazunis, Bingnan Wang, Koon Hoo Teo

This article discusses the use of metamaterials and resonator arrays to improve the range and efficiency of wireless power transfer, including both predicted and actual experimental results with single and multiple coupled resonators and metamaterial structures.



A Metamaterial-Inspired Combined Inductive-Capacitive Sensor

Citation: Long, J., Wang, B., "A Metamaterial-inspired Combined Inductive-capacitive Sensor", *SPIE Multisensor, Multisource Information Fusion: Architectures, Algorithms, and Applications*, Jerome J. Braun, Eds., DOI: 10.1117/12.2053318, ISBN: 9781628410587, May 2014, vol. 9121.

Contacts: Bingnan Wang

This paper reports a metamaterial inspired combined inductive-capacitive sensing method for detecting and distinguishing metallic and non-metallic objects. Metallic and non-metallic objects can be distinguished by measuring both of their inductive and capacitive responses based on the fact that they respond differently to inductive and capacitive sensing. The proposed method is inspired by metamaterial structures. Both inductive and capacitive sensing are simultaneously realized when the sensor is operating at off-resonant frequencies. The proposed method is demonstrated with typical printed circuit board (PCB) technology. The designed sensor can distinguish the metallic and dielectric objects with a sensing range about 10 mm, showing a competitive performance compared with commercially available proximity sensors.

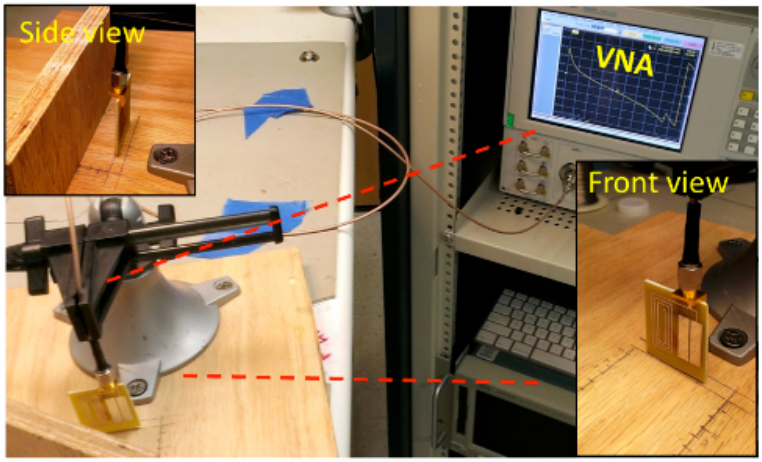


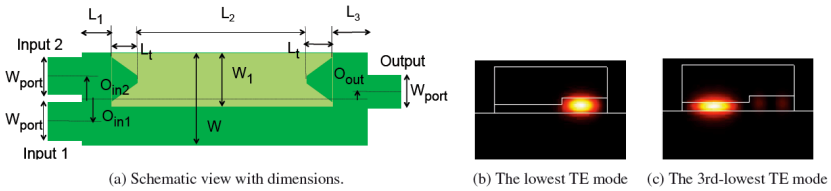
Figure 7. Experiment setup, with fabricated sensing structure shown in the inset.

An MMI-Based Wavelength Combiner Employing a Refractive Index Step

Citation: Kojima, K., Koike-Akino, T., Wang, B., Singh, S., Ozbayat, S., Parsons, K., Nishikawa, S., Yagyu, E, "An MMI-based Wavelength Combiner Employing a Refractive Index Step", *Integrated Photonics Research Silicon and Nanophotonics*, DOI: 10.1364/IPRSN.2014.JT4A.4, ISBN: 978-1-5552-737-0, July 2014.

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

A novel wavelength combiner using a refractive index step within a multimode interference device is proposed and simulated. An InP-based 1.30/1.31 um combiner has a length of 1272 um and an insertion loss of 0.6 dB.



(a) Schematic view with dimensions. (b) The lowest TE mode (c) The 3rd-lowest TE mode

Fig. 3. Simplified two beam combiner structure and modes at the MMI cross-section.

Application of Numerical Optimization to the Design of InP-based Wavelength Combiners

Citation: Ozbayat, S., Kojima, K., Koike-Akino, T., Wang, B., Parsons, K., Singh, S., Nishikawa, S., Yagyu, E., "Application of Numerical Optimization to the Design of InP-based Wavelength Combiners", *Optics Communications*, DOI: 10.1016/j.optcom.2014.02.030, ISSN: 0030-4018, Vol. 322, pp. 131-136, July 2014.

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

We applied a numerical device optimization scheme, where tens of parameters can be optimized simultaneously with multiple target performance criteria that are given. The key items of the design scheme are the selection of the best optimization algorithm, metric, and consideration for fabrication errors. This method was then applied to design an MMI beam combiner with rectangular effective refractive steps with up to 75 parameters, and we obtained a simulated insertion loss of 0.8 dB for a 1.4 mm-long 2x1 wavelength combiner, and a simulated insertion loss of 4.2 dB for a 1.9 mm-long 4x1 wavelength combiner, both with 20 nm wavelength spacing. This methodology could also be applied to other types of optical devices.

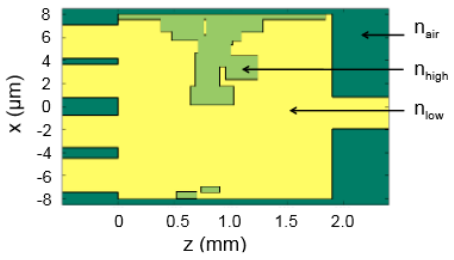


Figure 11: Effective refractive indes distribution of the optimized 4×1 wavelength combiner with 16 patches.

Transceiver-Limited High Spectral Efficiency Nyquist-WDM Systems

Citation: Millar, D.S., Maher, R., Lavery, D., Koike-Akino, T., Alvarado, A., Paskov, M., Kojima, K., Parsons, K., Li, R., Savory, S.J., Bayvel, P., "Transceiver-Limited High Spectral Efficiency Nyquist-WDM Systems", *Optical Fiber Communication Conference (OFC)*, DOI: 10.1364/OFC.2015.Th2A.13, ISBN: 978-1-55752-937-4, March 2015.

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

We experimentally examine the maximum achievable transmission performance of a 7 channel Nyquist-WDM system with 10GBd per carrier. Back-to-back, a maximum of 11.9 bit/sym and 13.8 bit/sym can be transmitted for DP-64QAM and DP-256QAM respectively, while after 2 spans of transmission, a maximum of 12.4 bit/sym and 11.6 bit/sym can be achieved.

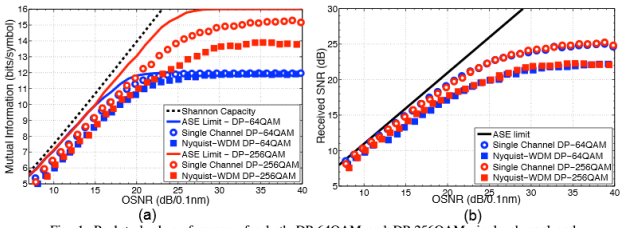


Fig. 1. Back-to-back performance for both DP-64QAM and DP-256QAM single channel and Nyquist-WDM. Mutual information is presented in (a), while evolution of received SNR with OSNR is shown in (b).

Reliable Routing in Large Scale Wireless Sensor Networks

Citation: Guo, J., Orlik, P.V., Zhang, J., Ishibashi, K., "Reliable Routing in Large Scale Wireless Sensor Networks", *International Conference on Ubiquitous and Future Networks (ICUFN)*, DOI: 10.1109/ICUFN.2014.6876758, pp. 99- 104, July 2014.

Contacts: Jianlin Guo, Philip V. Orlik, Jinyun Zhang

Wireless sensor networks have a wide range of applications including target detection and tracking, environment monitoring, industrial process monitoring, hospital monitoring, and public utility service. A sensor network consists of a large number of sensor nodes and a few sink nodes to collect data from sensor nodes. Sensor nodes and sink nodes form a large scale wireless mesh network in which packets are typically delivered between sensor nodes and sink nodes in a multi-hop manner. Reliable packet routing in wireless sensor networks is crucial, especially when network size is large. This paper presents a reliable routing protocol (RRP) to maximize the reliability of data collection and control command delivery in large scale wireless sensor networks. RRP aims to discover multiple bidirectional routes between a sensor node and a sink node. Sink node initiates route construction with an imaginary node as the destination to guarantee complete routing topology buildup. RRP achieves load balance by sending data packets via the route with lighter workload. RRP can be optimized for lightweight routing. Simulation results show that the proposed RRP routing protocol can realize 100% of packet delivery rate and outperforms existing routing protocols in terms of packet delivery rate, routing packet overhead, and end-to-end packet delay.

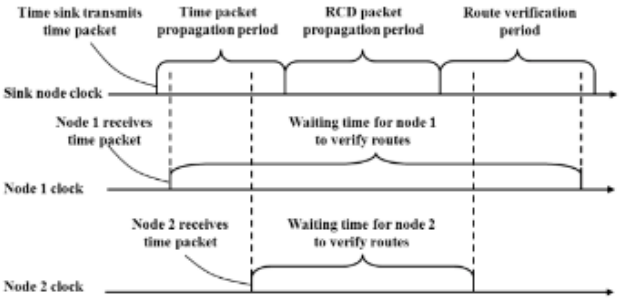


Figure 5. Route Verification Scheduling Example

A Fully Analog Two-way Sequential GaN Power Amplifier with 40% Fractional Bandwidth

Citation: Shao, J., Ma, R., Teo, K.H., Shinjo, S., Yamanaka, K., "A Fully Analog Two-way Sequential GaN Power Amplifier with 40% Fractional Bandwidth", *IEEE MTT-S International Wireless Symposium (IWS)*, March 2015.

Contacts: Rui Ma, Koon Hoo Teo

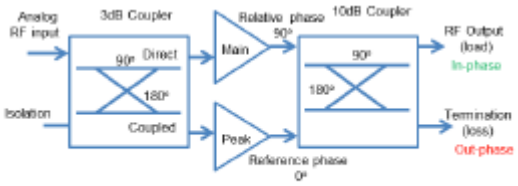


Fig. 1. Schematic of the proposed two-way SPA.

In this paper, we report a two-way sequential power amplifier (SPA) using GaN HEMTs. The proposed fully analog SPA delivers Past of approximately 40dBm over 2-3 GHz covering 40% fractional bandwidth. The design consists of a 3dB input coupler, a main amplifier, a peak amplifier, and a 10dB output coupler for power combining. After proper designing and optimizing these critical wideband couplers in terms of both phase and amplitude alignment, the measured final SPA shows 45% to 61% drain efficiency (DE) at 34dBm (5dB backoff) output from 2.1 to 2.9 GHz under CW stimulus. A complete set of SPA with analog RF input and output network is demonstrated.

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

Dual System Combination Approach for Various Reverberant Environments with Dereverberation Techniques

Citation: Tachioka, Y., Narita, T., Weninger, F., Watanabe, S., "Dual system combination approach for various reverberant environments with dereverberation techniques", *IEEE REVERB Workshop*, May 2014.

Contacts: Shinji Watanabe

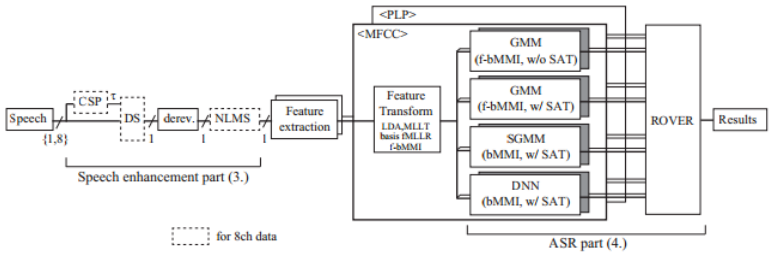


Fig. 1. Schematic diagram of the proposed system. (CSP: cross spectrum phase analysis, DS: delay-and-sum beamformer, derev.: proposed dereverberation method, NLMS: normalized least-mean-squares algorithm, gray blocks are complementary systems for each system type)

We focus on state-of-the-art ASR techniques such as discriminative training and various feature trans- formations including Gaussian mixture model, sub-space Gaussian mixture model, and deep neural networks, in addition to the pro- posed single channel dereverberation method with reverberation time estimation and multi-channel beamforming that enhances direct sound compared with the reflected sound. In addition, because the best performing system is different from environment to environment, we perform a system combination approach using different feature and different types of systems to handle these various environments in the challenge. Experiments show the effectiveness of these approaches, reaching 6.76% and 18.60% word error rate on the REVERB simulated and real test sets, which are 68.8% and 61.5% relative improvements over the baseline.

Log-linear Dialog Manager

Citation: Tang, H., Watanabe, S., Marks, T.K., Hershey, J.R., "Log-linear Dialog Manager", *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, DOI: 10.1109/ICASSP.2014.6854371, May 2014, pp. 4092-4096.

Contacts: Shinji Watanabe, Tim K. Marks, John R. Hershey

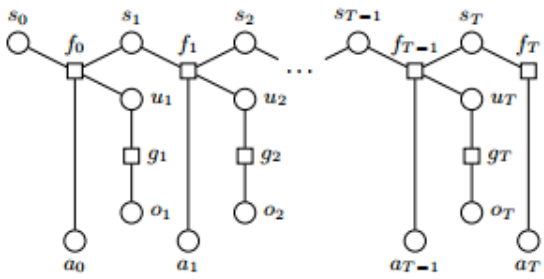


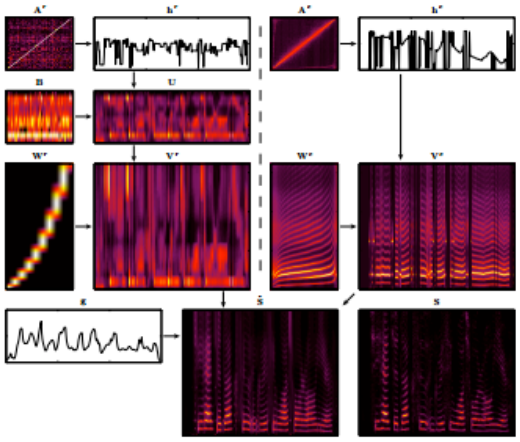
Fig. 1. The factor graph representation for the distribution in (1).

We design a log-linear probabilistic model for solving the dialog management task. In both planning and learning we optimize the same objective function: the expected reward. Rather than performing full policy optimization, we perform on-line estimation of the optimal action as a belief-propagation inference step. We employ context-free grammars to describe our variable spaces, which enables us to define rich features. To scale our approach to large variable spaces, we use particle belief propagation. Experiments show that the model is able to choose system actions that yield a high expected reward, outperforming its POMDP-like log-linear counterpart and a hand-crafted rule-based system.

Non-negative Source-filter Dynamical System for Speech Enhancement

Citation: Simsekli, U., Le Roux, J., Hershey, J.R., "Non-negative Source-filter Dynamical System for Speech Enhancement", *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, DOI: 10.1109/ICASSP.2014.6854797, May 2014, pp. 6206-6210.

Contacts: Jonathan Le Roux, John R. Hershey

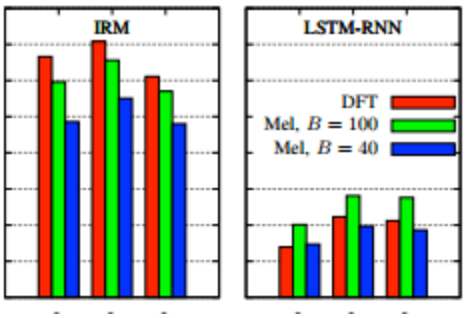


Model-based speech enhancement methods, which rely on separately modeling the speech and the noise, have been shown to be powerful in many different problem settings. When the structure of the noise can be arbitrary, which is often the case in practice, model-based methods have to focus on developing good speech models, whose quality will be key to their performance. In this study, we propose a novel probabilistic model for speech enhancement which precisely models the speech by taking into account the underlying speech production process as well as its dynamics. The proposed model follows a source-filter approach where the excitation and filter parts are modeled as non-negative dynamical systems. We show that our model outperforms state-of-the-art methods in terms of objective measures.

Discriminatively Trained Recurrent Neural Networks for Single-Channel Speech Separation

Citation: Weninger, F., Le Roux, J., Hershey, J.R., Schuller, B., "Discriminatively Trained Recurrent Neural Networks for Single-Channel Speech Separation", IEEE Global Conference on Signal and Information Processing (GlobalSIP), DOI: 10.1109/GlobalSIP.2014.7032183, December 2014, pp. 577-581.

Contacts: Jonathan Le Roux, John R. Hershey



This paper describes an in-depth investigation of training criteria, network architectures and feature representations for regression-based single-channel speech separation with deep neural networks (DNNs). We use a generic discriminative training criterion corresponding to optimal source reconstruction from time-frequency masks, and introduce its application to speech separation in a reduced feature space. A comparative evaluation of time-frequency mask estimation by DNNs, recurrent DNNs and non-negative matrix factorization on the 2nd CHiME Speech Separation and Recognition Challenge shows consistent improvements by discriminative training, whereas long short-term memory recurrent DNNs obtain the overall best results. Our results confirm the importance of fine-tuning the feature representation for DNN training.

Deep Recurrent De-noising Auto-encoder and Blind De-reverberation for Reverberated Speech Recognition

Citation: Weninger, F., Watanabe, S., Tachioka, Y., Schuller, B., "Deep Recurrent De-noising Auto-encoder and Blind De-reverberation for Reverberated Speech Recognition", *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP),* DOI: 10.1109/ICASSP.2014.6854478, May 2014, pp. 4623-4627.

Contacts: Shinji Watanabe

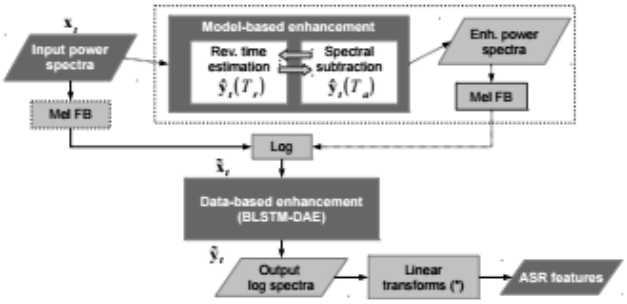


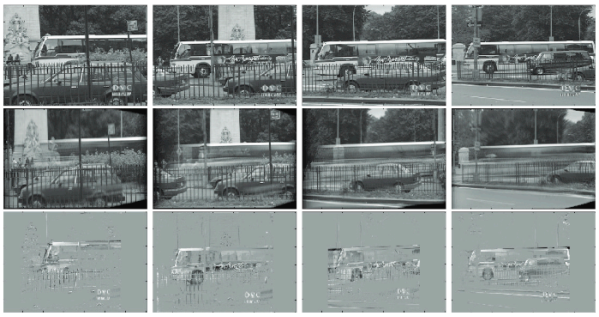
Fig. 1: Flowchart of the proposed method. Dashed lines depict optional processing steps. FB: filterbank. (*) Linear transformations: DCT (to obtain MFCC), LDA, MLLT, CMLLR – see text.

This paper describes our joint efforts to provide robust automatic speech recognition (ASR) for reverberated environments, such as in hands-free human-machine interaction. We investigate blind feature space de-reverberation and deep recurrent de-noising auto-encoders (DAE) in an early fusion scheme. Results on the 2014 REVERB Challenge development set indicate that the DAE front-end provides complementary performance gains to multi-condition training, feature transformations, and model adaptation. The proposed ASR system achieves word error rates of 17.62 % and 36.6 % on simulated and real data, which is a significant improvement over the Challenge baseline (25.16 and 47.2 %).

Video Background Subtraction using Semi-supervised Robust Matrix Completion

Citation: Mansour, H., Vetro, A., "Video Background Subtraction Using Semi-supervised Robust Matrix Completion", *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP),* DOI: 10.1109/ICASSP.2014.6854862, May 2014, pp. 6528-6532.

Contacts: Hassan Mansour, Anthony Vetro



We propose a factorized robust matrix completion (FRMC) algorithm with global motion compensation to solve the video background subtraction problem. The algorithm decomposes a sequence of video frames into the sum of a low rank background component and a sparse motion component. For videos with moving background, we utilize the motion vectors extracted from the coded video bitstream to compensate for the change in the camera perspective. Performance evaluations show that our approach is faster than state-of- the-art solvers and results in highly accurate motion segmentation.

Video Querying Via Compact Descriptors of Visually Salient Objects

Citation: Mansour, H., Rane, S., Boufounos, P.T., Vetro, A., "Video Querying Via Compact Descriptors of Visually Salient Objects", *IEEE International Conference on Image Processing (ICIP)*, DOI: 10.1109/ICIP.2014.7025564, October 2014, pp. 2789-2793.

Contacts: Hassan Mansour, Petros T. Boufounos, Anthony Vetro

We consider the problem of extracting descriptors that represent visually salient portions of a video sequence. Most state-of-the-art schemes generate video descriptors by extracting features, e.g., SIFT or SURF or other keypoint-based features, from individual video frames. This approach is wasteful in scenarios that impose constraints on storage, communication overhead and on the allowable computational complexity for video querying. More importantly, the descriptors obtained by this approach generally do not provide semantic clues about the video content. In this paper, we investigate new feature-agnostic approaches for efficient retrieval of similar video content. We evaluate the efficiency and accuracy of retrieval when k-means clustering is applied to image features extracted from video frames.

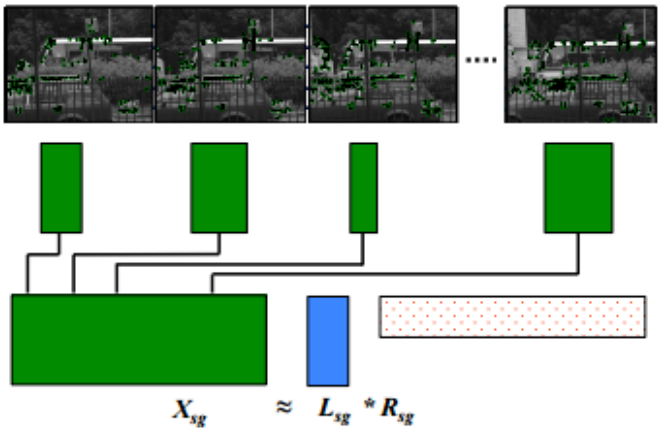


Fig. 1: Example of extracting SIFT features from a video scene and computing the compact descriptor L along with the binary selection matrix R.

An Elementary Completeness Proof for Secure Two-Party Computation Primitives

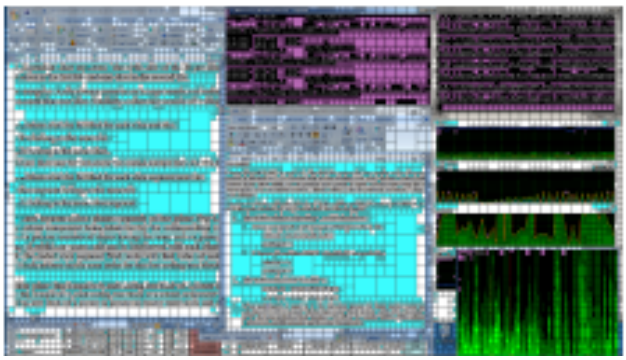
Citation: Wang, Y.; Ishwar, P.; Rane, S., "An Elementary Completeness Proof for Secure Two-party Computation Primitives", IEEE Information Theory Workshop (ITW), DOI: 10.1109/ITW.2014.6970886, ISSN: 1662-9019, pp. 521-525, November 2014.

Contacts: Ye Wang

In the secure two-party computation problem, two parties wish to compute a (possibly randomized) function of their inputs via an interactive protocol, while ensuring that neither party learns more than what can be inferred from only their own input and output. For semi-honest parties and information-theoretic security guarantees, it is well-known that, if only noise-less communication is available, only a limited set of functions can be securely computed; however, if interaction is also allowed over general communication primitives (multi-input/output channels), there are 'complete' primitives that enable any function to be securely computed. The general set of complete primitives was characterized recently by Maji, Prabhakaran, and Rosulek leveraging an earlier specialized characterization by Kilian. Our contribution in this paper is a simple, self-contained, alternative derivation using elementary information-theoretic tools.

Independent Uniform Prediction Mode for Screen Content Video Coding

Citation: Zhang, X., Cohen, R.A., Vetro, A., "Independent Uniform Prediction Mode for Screen Content Video Coding", *IEEE Visual Communications and Image Processing Conference ,* DOI: 10.1109/VCIP.2014.7051521, ISBN: 978-1-4799-6139-9, December 2014, pp. 129-132.
Contacts: Robert A. Cohen, Anthony Vetro



Many of the existing video coding standards in use today were developed primarily using camera-captured content as test material. Today, with the more widespread use of connected devices, there is an increased interest in developing video coding tools that target screen content video. Screen content video is often characterized by having sharp edges, noiseless graphics-generated regions, repeated patterns, limited sets of colors, etc. This paper presents an independent uniform prediction (IUP) mode for improving the coding efficiency of screen content video. IUP chooses one color out of a small set of global colors to form a uniform prediction block. Experimental results using IUP in the HEVC Range Extensions 6.0 framework are presented, along with results using techniques that reduce complexity so that the IUP-based encoder is faster than the reference encoder.

Chebyshev and Conjugate Gradient Filters for Graph Image Denoising

Citation: Tian, D., Knyazev, A., Mansour, H., Vetro, A., "Chebyshev and Conjugate Gradient Filters for Graph Image Denoising", *IEEE International Conference on Multimedia and Expo Workshops (ICMEW)*, DOI: 10.1109/ICMEW.2014.6890711, ISSN: 1945-7871, July 2014, pp. 1-6.
Contacts: Dong Tian, Andrew Knyazev, Hassan Mansour, Anthony Vetro

In 3D image/video acquisition, different views are often captured with varying noise levels across the views. In this paper, we propose a graph-based image enhancement technique that uses a higher quality view to enhance a degraded view. A depth map is utilized as auxiliary information to match the perspectives of the two views. Our method performs graph-based filtering of the noisy image by directly computing a projection of the image to be filtered onto a lower dimensional Krylov subspace of the graph Laplacian. We discuss two graph spectral denoising methods. Our framework generalizes previously known polynomial graph filters, and we demonstrate through numerical simulations that our proposed technique produces subjectively cleaner images with about 13 dB improvement in PSNR over existing polynomial graph filters.

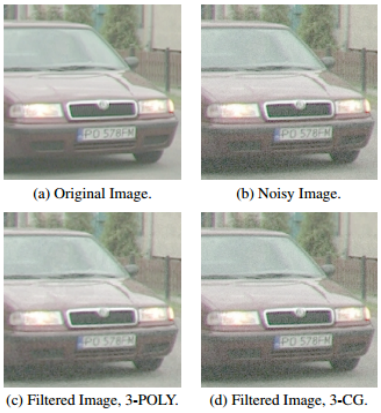


Fig. 4: Comparison of filtered images.

Sparse MIMO Architectures for Through-the-wall Imaging

Citation: Li, L, Boufounos, P.T., Liu, D., Mansour, H., Sahinoglu, S., "Sparse MIMO Architectures For Through-the-wall Imaging", *IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM),* DOI: 10.1109/SAM.2014.6882455, June 2014, pp. 513 - 516.

Contacts: Petros T. Boufounos, Dehong Liu, Hassan Mansour, Zafer Sahinoglu

This paper explores the potential of sparse Multiple-Input-Multiple-Output (MIMO) radar arrays to significantly reduce the cost of through-the-wall imaging (TWI). We analyze three well-known sparse array structures (nested arrays, co-prime arrays and random arrays) and examine their performance in the presence of common types of layered walls. The reconstruction is performed by formulating and solving a wall parameter estimation problem in conjunction with a sparse reconstruction problem that takes the wall parameters into account.

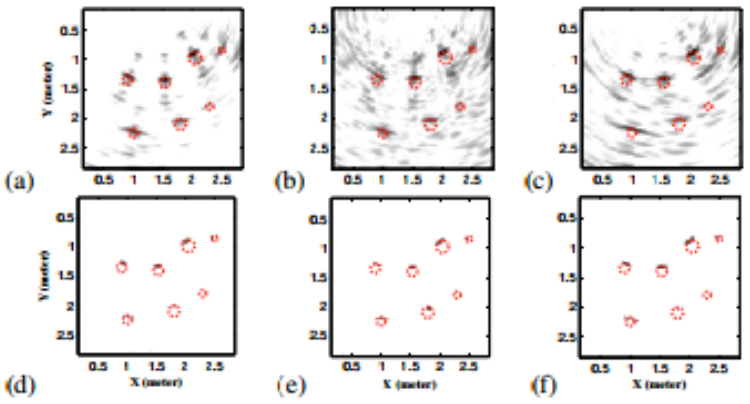


Fig. 6. Reconstructed image from FDTD simulations. (a)–(c) backprojection, (d)–(e) sparse reconstruction.

Compressive Sensing Based 3D SAR Imaging with Multi-PRF Baselines

Citation: Liu, D., Boufounos, P.T., "Compressive Sensing Based 3D SAR Imaging with Multi-PRF Baselines", *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, DOI: 10.1109/IGARSS.2014.6946672, July 2014, pp. 1301-1304.

Contacts: Dehong Liu, Petros T. Boufounos

In this paper, we fundamentally re-examine 3D SAR imaging and propose a CS-based approach aiming to reduce the data collection cost and increase the elevation resolution. In particular, our approach significantly reduces the number of baselines required to acquire the scene of interest, as well as the pulsing rate in each baseline. Using the collected multi-baseline data in its entirety we generate a high resolution 3D reflectivity map, using a CS-based iterative imaging algorithm. Our simulation results demonstrate that the proposed method can improve elevation resolution significantly.

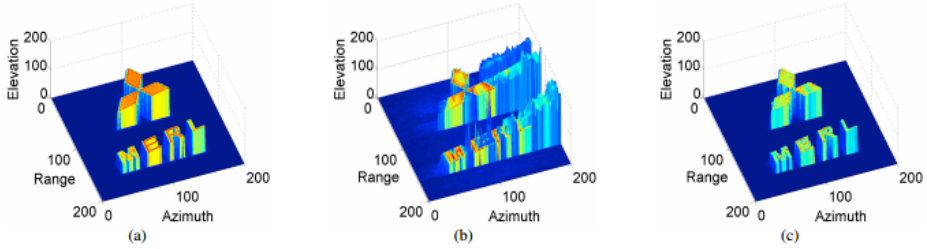


Fig. 4. (a) Reconstruction using data from 281 baselines at high PRF, (b) Conventional reconstruction with 28 baselines each with different, reduced PRF, and (c) CS-based reconstruction using the same limited data as (b).

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

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 U. 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.

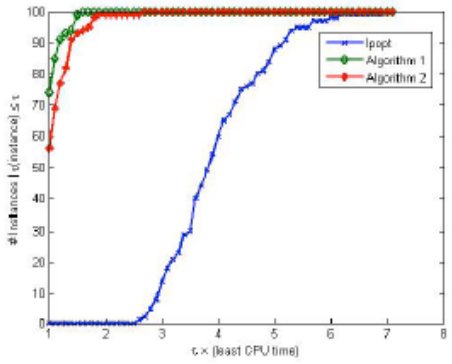


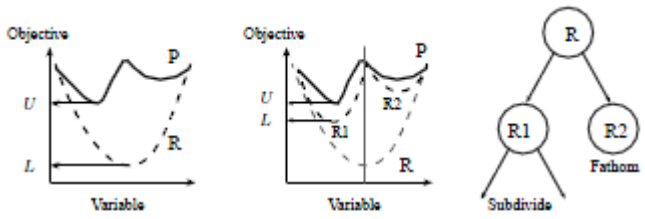
Fig. 4. Performance profiles of algorithms based on CPU time for convergence.

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 U. Raghunathan, Daniel N. 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 N. Nikovski

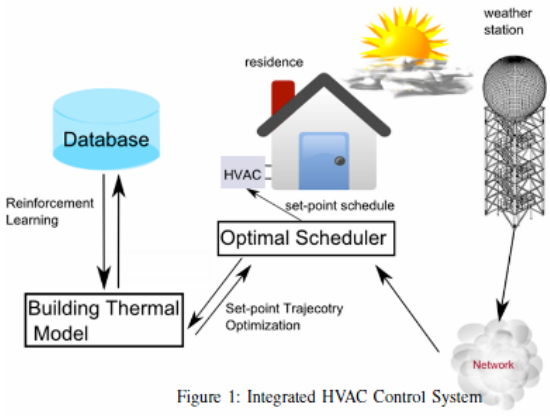


Figure 1: Integrated HVAC Control System

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 N. Nikovski

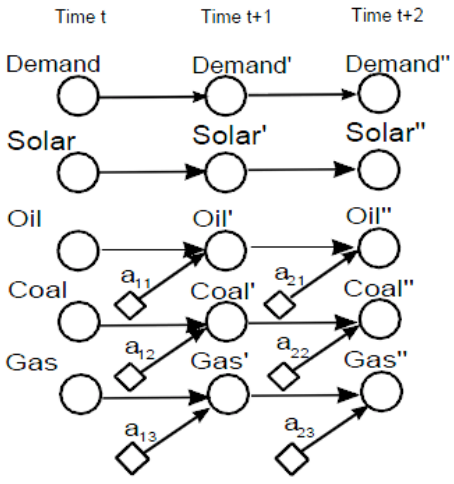


Figure 1: DBN for a power generation problem with three controllable and one uncontrollable power generators.

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.

Locating Double-line to Ground Faults using Hybrid Current Profile Approach

Citation: Dubey, A., Sun, H., Nikovski, D.N., Tomihiro, T., Kojima, Y., Tetsufumi, O., "Locating Double-line-to-ground Faults using Hybrid Current Profile Approach", *IEEE PES Conference on Innovative Smart Grid Technologies (ISGT)*, February 2015.
Contacts: Hongbo Sun, Daniel N. Nikovski

This paper proposes a hybrid current profile based fault location algorithm for double-line-to-ground (DLG) faults in a distribution system. The method uses both short-circuit fault current profile (average of fault currents recorded for the faulted phases) and during-fault load current profile (corresponding to the un-faulted phase) to estimate an accurate fault location. The method is extended to include the effects of fault resistance in determining the fault location. Both fault current profiles and load current profiles are simulated for different values of fault resistances. The profiles are also extrapolated for those fault resistances corresponding to which the simulated profiles are not available. Numerical examples on a sample distribution feeder with multiple laterals and load taps are provided to validate the proposed algorithm for its robustness.

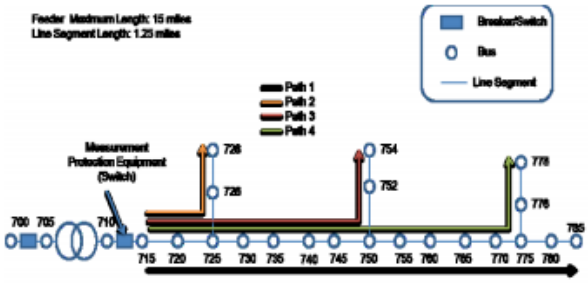


Figure 1. Simulated single-feeder test distribution circuit

Electricity Theft Detection Using Smart Meter Data

Citation: Sahoo, S., Nikovski, D.N., Muso, T., Tsuru, K., "Electricity Theft Detection Using Smart Meter Data", *IEEE PES Conference on Innovative Smart Grid Technologies (ISGT),* February 2015.
Contacts: Daniel N. Nikovski

Electricity theft is a major concern for the utilities. With the advent of smart meters, the frequency of collecting household energy consumption data has increased, making it possible for advanced data analysis, which was not possible earlier. We have proposed a temperature dependent predictive model which uses smart meter data and data from distribution transformer to detect electricity theft in an area. The model was tested for varying amounts of power thefts and also for different types of circuit approximations. The results are encouraging and the model can be used for real world application.

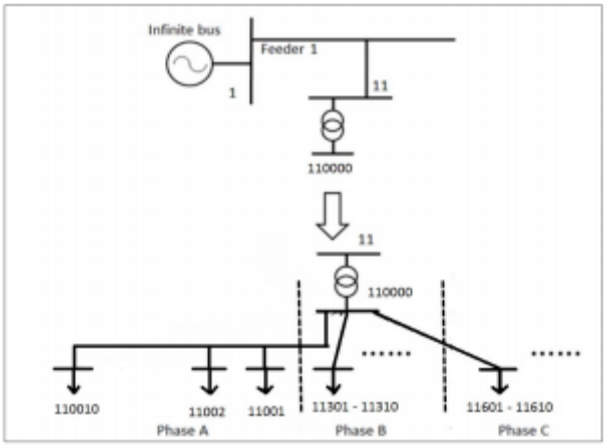


Fig. 3: Linear approximation of distribution circuit

Infeasibility Detection in Alternating Direction Method of Multipliers for Convex Quadratic Programs

Citation: Raghunathan, A. U., Di Cairano, S., "Infeasibility Detection in Alternating Direction Method of Multipliers for Convex Quadratic Programs", *IEEE Conference on Decision and Control (CDC),* DOI: 10.1109/CDC.2014.7040300, ISBN: 978-1-4799-7746-8, December 2014, pp. 5819-5824.

Contacts: Arvind U. Raghunathan, Stefano Di Cairano

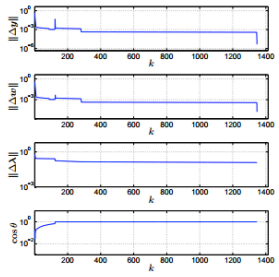


Fig. 1. Example: infeasible QP of MPC of a spacecraft with flexible appendage subject to constraints: evolution of the norm of the ADMM iterates variables/variable differences.

We investigate infeasibility detection in the alternating direction method of multipliers (ADMM) when minimizing a convex quadratic objective subject to linear equalities and simple bounds. The ADMM formulation consists of alternating between an equality constrained quadratic program (QP) and a projection onto the bounds. We show that: (i) the sequence of iterates generated by ADMM diverges, (ii) the divergence is restricted to the component of the multipliers along the range space of the constraints and (iii) the primal iterates converge to a minimizer of the Euclidean distance between the subspace defined by equality constraints and the convex set defined by bounds. In addition, we derive the optimal value for the step size parameter in the ADMM algorithm that maximizes the rate of convergence of the primal iterates and dual iterates along the null space.

Distributed Three-phase Reactive Power Control of Distributed Energy Resources in Distribution Systems

Citation: Sun, H., Benosman, M., Nikovski, D., Zhang, J., Takano, T., Kojima, Y., Ohno, T., "Distributed Three-phase Reactive Power Control of Distributed Energy Resources in Distribution Systems", *International Conference on Power System Technology (POWERCON),* DOI: 10.1109/POWERCON.2014.6993980, October 2014, pp. 2549-2556.

Contacts: Hongbo Sun, Mouhacine Benosman, Daniel Nikovski, Jinyun Zhang

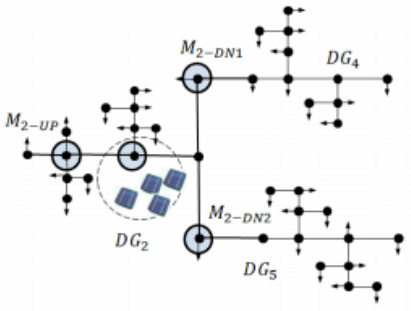


Fig. 2. An example of monitored buses for a DER-connected bus

This paper proposes a new distributed control method for three-phase reactive power control of distributed energy resources (DERs) in distribution systems. Each DER-connected bus has been equipped with a local bus controller, which has bi-way communications with bus controllers at adjacent buses upstream and downstream to the bus under consideration. The reactive powers of a DER-connected bus are adjusted to prevent its monitored buses from voltage violations. When voltage violations occur, the required reactive powers for the bus are determined based on the voltage violations on its monitored buses, and equivalent impedances and phase angle shifting between the substation transformer and the study bus. A consensus-based distributed control algorithm is used to allocate the total demand among units with respect to their capacities.

A Comparison of Transient Heat Pump Cycle Simulations with Homogeneous and Heterogeneous Flow Models

Citation: Laughman, C.R., "A Comparison of Transient Heat-pump Cycle Simulations with Homogeneous and Heterogeneous Flow Models", *International Refrigeration and Air Conditioning Conference,* July 2014, pp. 1-10.

Contacts: Christopher R. Laughman

This paper compares two alternative approaches to the transient simulation of vapor-compression air-conditioning cycles that use different descriptions of the thermofluid behavior on the refrigerant side of the heat exchangers. While one of the most common modeling assumptions for two-phase refrigerant flow in transient cycle simulation is that the liquid and gas phases travel at the same velocity, a condition that is referred to as homogeneous flow, the two phases in real heat exchangers in vapor-compression cycles move at different velocities, requiring a heterogeneous flow model.

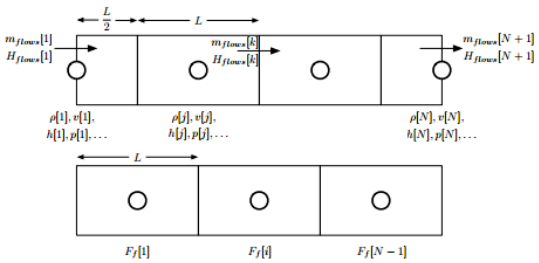


Figure 1: The staggered grids used to solve the balance equations.

Optimal Step-Size Selection in Alternating Direction Method of Multipliers for Convex Quadratic Programs and Model Predictive Control

Citation: Raghunathan, A. U., Di Cairano, S., "Optimal Step-size Selection in Alternating Direction Method of Multipliers for Convex Quadratic Programs and Model Predictive Control", *International Symposium on Mathematical Theory of Networks and Systems (MTNS)*, ISBN: 978-90-367-6321-9, July 2014, pp. 807-814.

Contacts: Arvind U. Raghanathan, Stefano Di Cairano

In this paper we propose an approach for solving convex quadratic programs (QPs) with linear equalities and general linear inequalities by the alternating direction method of multipliers (ADMM). ADMM has attracted considerable interest in recent years in different application fields, especially due to the simplicity of the iteration. We focus on the application of ADMM to the QPs that are solved in Model Predictive Control (MPC) algorithms, where the inequalities represent limits on the states and controls. After introducing our ADMM iteration, we provide a proof of convergence based on the theory of maximal monotone operators. The proving approach allows us to identify a more general measure to monitor the rate of convergence than those previously used and to characterize the optimal step size for the ADMM iterations for the considered class of QPs. While the mathematical result has a similar structure to previous contributions, it allows us to relax some of the previously required assumptions that currently limit the applicability to the QP of model predictive control.

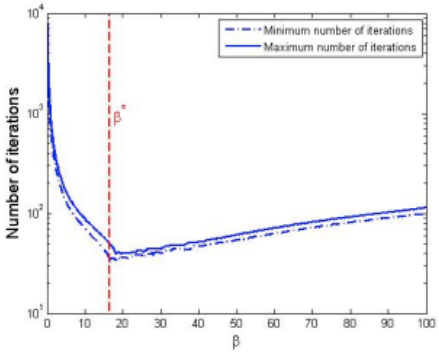


Fig. 1. Plot of minimum and maximum number of iterations to attain convergence over the set of 170 QPs for different values of the step size β for the algorithm proposed in this paper.

Minimizing energy consumption in railways by voltage control on substations

Citation: Raghunathan, A. U., Wada, T., Ueda, K., Takahashi, S., "Minimizing Energy Consumption in Railways by Voltage Control on Substations", *WIT Transactions of the Built Environment,* DOI: 10.2495/CR140581, June 2014.
Contacts: Arvind U. Raghunathan

We propose an optimization method for minimizing energy consumption in DCelectrified railways where the trains are fitted with regenerative brakes. Reduction in energy consumption is achieved by controlling the voltage at the substations in real time. Conditional constraints are employed to model the behavior of trains and substations. This allows us to relax some of the imposed limits thereby enlarging the operating envelope of system and increasing the potential for energy savings. The conditional constraints are modeled using complementarity constraints which are smooth and differentiable. The optimization problem is an instance of a Mathematical Program with Equilibrium Constraints (MPEC). A numerical example with 42 trains and 8 substations is used to illustrate the savings from the method and the computational times.

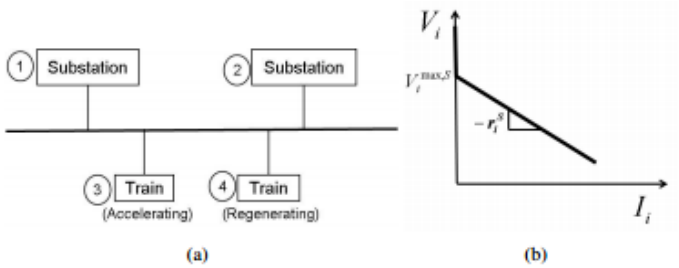


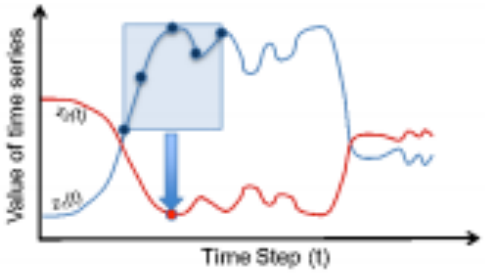
Figure 2: (a) Graph representation of the network. In this case, $\mathcal{N} = \{1,2,3,4\}$, and $\mathcal{L} = \{(1,3),(3,4),(4,2)\}$. Further, $\mathcal{N}^S = \{1,2\}$, $\mathcal{N}^A = \{3\}$, $\mathcal{N}^R = \{4\}$. (b) Voltage-current characteristic of an uncontrolled substation.

The proposed approach is shown to reduce energy consumption by about 3% over 2:5 minute of operation, recover about 97% of the regenerated energy while computing the optimal voltages in real time (< 1s).

Anomaly Detection in Real-Valued Multidimensional Time Series

Citation: Jones, M., Nikovski, D. N., Imamura, M., Hirata, T., "Anomaly Detection in Real-valued Multidimensional Time Series", *ASE Bigdata/Socialcom/Cyber Security Conference,* ISBN: 978-1-62561-000-3, June 2014.
Contacts: Michael Jones, Daniel N. Nikovski

We present a new algorithm for detecting anomalies in real valued multidimensional time series. Our algorithm uses an exemplar-based model that is used to detect anomalies in single dimensions of the time series and a function that predicts one dimension from a related one to detect anomalies in multiple dimensions. The algorithm is shown to work on a variety of different types of time series as well as to detect a variety of different types of anomalies. We compare our algorithm to other algorithms for both one-dimensional and multidimensional time series and demonstrate that it improves over the state-of-the-art.



Alternating direction method of multipliers for strictly convex quadratic programs: Optimal parameter selection

Citation: Raghunathan, A.U., Di Cairano, S., "Alternating Direction Method of Multipliers for Strictly Convex Quadratic Programs: Optimal Parameter Selection", *American Control Conference (ACC)*, DOI: 10.1109/ACC.2014.6859093, ISSN: 0743-1619, ISBN: 978-1-4799-3272-6, June 2014, pp. 4324-4329.

Contacts: Arvind U. Raghunathan, Stefano Di Cairano

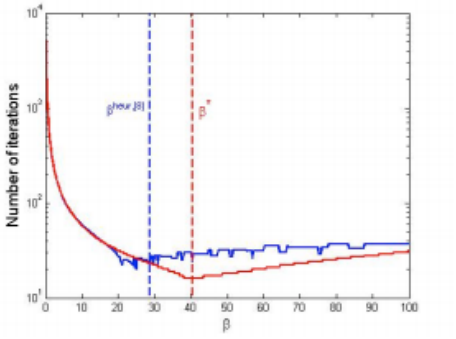


Fig. 1. Plot of number of iterations for convergence against the step-size β for the ADMM algorithm in [6] in blue and our approach in red. The dotted blue line indicates the heuristic value proposed in [6] while the red dotted line indicates the $\beta^\star$ from (16).

We consider an approach for solving strictly convex quadratic programs (QPs) with general linear inequalities by the alternating direction method of multipliers (ADMM). In particular, we focus on the application of ADMM to the QPs of constrained Model Predictive Control (MPC). After introducing our ADMM iteration, we provide a proof of convergence closely related to the theory of maximal monotone operators. The proof relies on a general measure to monitor the rate of convergence and hence to characterize the optimal step size for the iterations. We show that the identified measure converges at a Q-linear rate while the iterations converge at a 2-step Q-linear rate. This result allows us to relax some of the existing assumptions in optimal step size selection that currently limit the applicability of MPC to QPs.

Advanced Visual Interfaces for Smart Energy: Focusing Where it Matters Most

Citation: Wittenburg, K. B., Laughman, C., Nikovski, D. N., Sahinoglu, Z., "Advanced Visual Interfaces for Smart Energy: Focusing Where it Matters Most", *Workshop on Fostering Smart Energy Applications through Advanced Visual Interfaces,* DOI: 10.1145/2598153.2602224, ISSN: 1177-777X, May 2014, pp. 31-34.

Contacts: Kent B. Wittenburg, Christopher Laughman, Daniel N. Nikovski, Zafer Sahinoglu

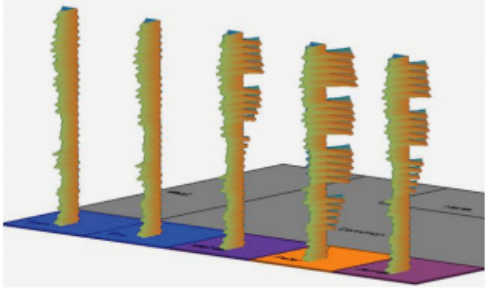


Figure 1: Visualization of cascading effects of an HVAC fault

Targeting reductions of electricity usage among consumers in their homes has been very popular among researchers, industry, and research funding organizations. Here we look behind the application surface to examine where visual energy-savings applications might have their greatest impact. We analyze residential, commercial, and industrial sectors in the US and observe differences regarding energy use, economic incentives, and leverage per establishment. We then give examples of industrial and commercial energy-savings applications being developed at Mitsubishi Electric and supported by its North American Research Laboratory, MERL.

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.

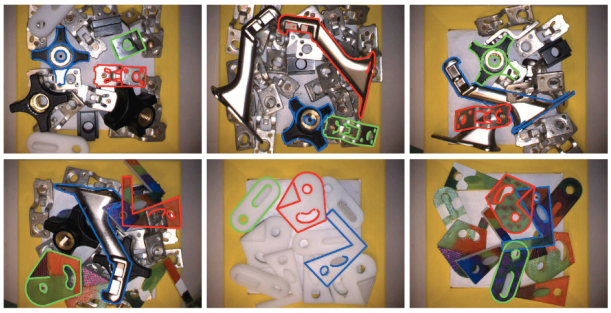
For many years, MERL has applied machine-learning methods to imaging problems of detection, classification, segmentation and understanding. A decade ago, the Viola-Jones algorithm for face detection was a good example. More recently we have been applying deep learning for semantic scene labeling and people detection/re-identification. We have freely blended our research in 3D and machine-learning to enable learning of the most effective features to use in 3D detection and estimation tasks.

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

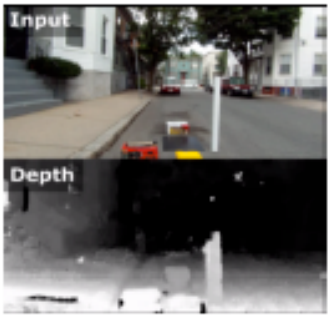


We present a practical vision-based robotic bin-picking system that performs detection and 3D pose estimation of objects in an unstructured bin using a novel camera design, picks up parts from the bin, and performs error detection and pose correction while the part is in the gripper. Two main innovations 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, Yuichi Taguchi



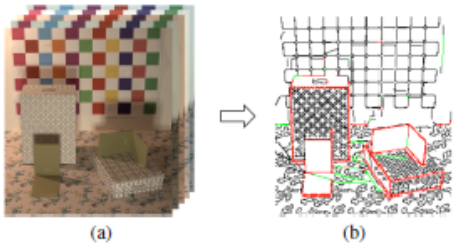
(c)

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

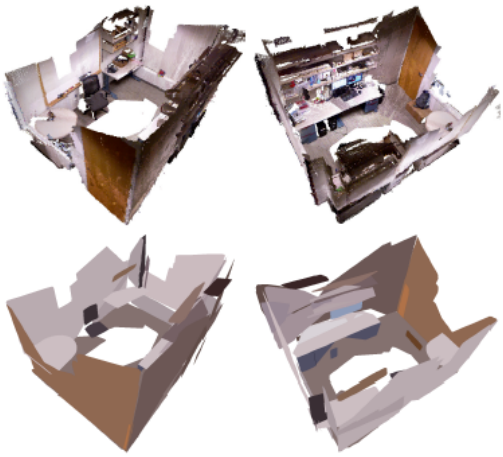


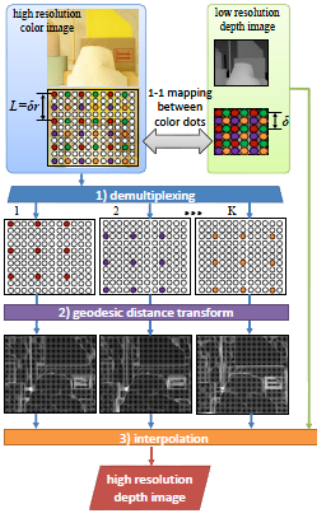
Fig. 1. A 3D model reconstructed from the sequence in Figure 4. Our system not only generates registered 3D point clouds (top), but also reconstructs a scene as a set of planes (bottom). Note that the plane-based model is obtained from plane landmarks, which are generated by our SLAM system in real time, 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-pair shortest-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

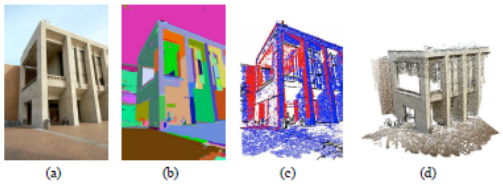


Fig. 7. Registering two point clouds, each generated by applying multi-view reconstruction techniques to 15 images. (a) One of the images used in 3D reconstruction. (b) superpixel segmentation of the image shown in (a). (c) The 3D points from the first (blue) and second (red) clouds are reprojected onto 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.

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

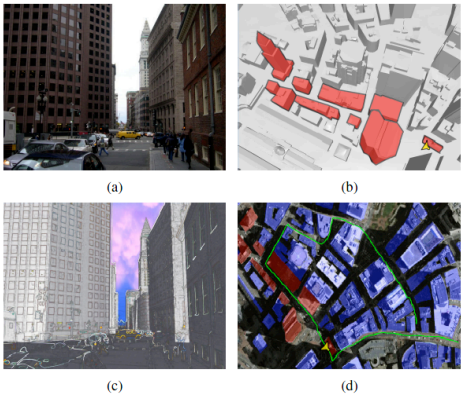
Fig. 9. Superpixel segmentation examples. The images contain 100 superpixels. The ground truth segments are color-coded and blended on the images. The superpixels (boundaries shown in white) respect object boundaries and tend to divide an image into similar-sized regions.

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.

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

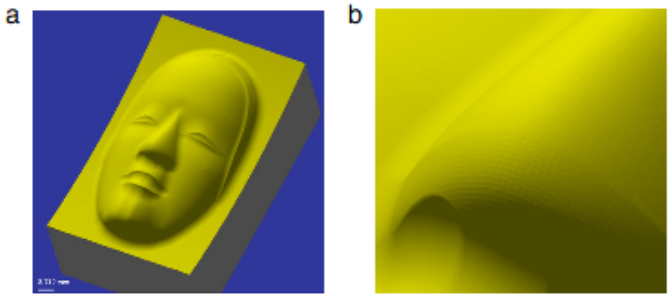
Citation: Ramalingam, S.; Pillai, J.K.; Jain, A.; Taguchi, Y., "Manhattan Junction Catalogue for Spatial Reasoning of Indoor Scenes", *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, DOI: 10.1109/CVPR. 2013. 394, ISSN: 1063-6919, pp. 3065-3072, June 2013
Contacts: Srikumar Ramalingam,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

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.

Recursive Context Propagation Network for Semantic Scene Labeling

Citation: Sharma, A., Tuzel, O., Liu, M.-Y., "Recursive Context Propagation Network for Semantic Scene Labeling", *Advances in Neural Information Processing Systems (NIPS)*, December 2014.
Contacts: Oncel Tuzel, Ming-Yu Liu

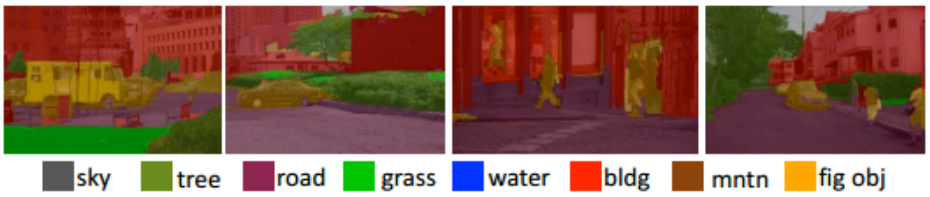
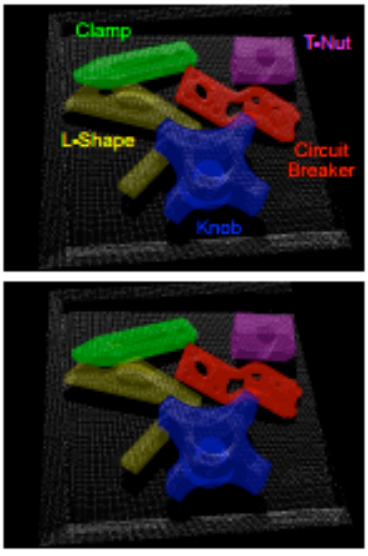


Figure 3: Typical labeling results on Stanford background dataset using our method

We propose a deep feed-forward neural network architecture for pixel-wise semantic scene labeling. It uses a novel recursive neural network architecture for context propagation, referred to as rCPN. It first maps the local visual features into a semantic space followed by a bottom-up aggregation of local information into a global representation of the entire image. Then a top-down propagation of the aggregated information takes place that enhances the contextual information of each local feature. Therefore, the information from every location in the image is propagated to every other location. Experimental results on Stanford background and SIFT Flow datasets show that the proposed method outperforms previous approaches.

Learning to Rank 3D Features

Citation: Tuzel, O., Liu, M-Y., Taguchi, Y., Raghunathan, A.U., "Learning to Rank 3D Features", *European Conference on Computer Vision (ECCV)*, DOI: 10.1007/978-3-319-10590-1_34, ISSN: 0302-9743, ISBN: 978-3-319-10589-5, September 2014, vol. 8689, pp. 520-535.
Contacts: Oncel Tuzel, Ming-Yu Liu, Yuichi Taguchi, Arvind Raghunathan



Representation of three-dimensional objects using a set of oriented point pair features has been shown to be effective for object recognition and pose estimation. Combined with an efficient voting scheme on a generalized Hough space, existing approaches achieve good recognition accuracy and fast operation. However, the performance of these approaches degrades when the objects are (self-)similar or exhibit degeneracies, such as large planar surfaces which are very common in both man-made and natural shapes, or due to heavy object and background clutter. We propose a max-margin learning framework to identify discriminative features on the surface of three-dimensional objects. Our algorithm selects and ranks features according to their importance for the specified task, which leads to improved accuracy and reduced computational cost. In addition, we analyze various grouping and optimization strategies to learn the discriminative pair features. We present extensive synthetic and real experiments demonstrating the improved results.

Improving Person Tracking Using an Inexpensive Thermal Infrared Sensor

Citation: Kumar, S., Marks, T.K., Jones, M., "Improving Person Tracking Using an Inexpensive Thermal Infrared Sensor", *IEEE Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, DOI: 10.1109/CVPRW.2014.41, June 2014, pp. 217-224.
Contacts: Tim Marks, Michael Jones

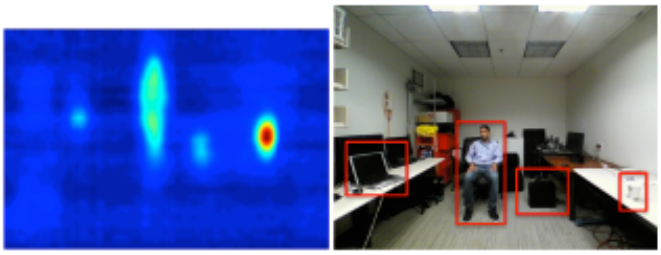


Figure 1: An image from our low-cost IR sensor (left) and a corresponding image from the RGB camera. The four blobs in the IR image correspond to (left to right): a laptop computer, a person, a CPU tower, and a cup of tea

This paper proposes a person-tracking framework using a scanning low-resolution thermal infrared (IR) sensor co-located with a wide-angle RGB camera. The low temporal and spatial resolution of the low-cost IR sensor make it unable to track moving people and prone to false detections of stationary people. Thus, IR-only tracking using only this sensor would be quite problematic. We demonstrate that despite the limited capabilities of this low-cost IR sensor, it can be used effectively to correct the errors of a real-time RGB camera-based tracker. Our combined RGB+IR system improves upon the RGB camera-only tracking by: rejecting false positives, improving segmentation of tracked objects, and correcting false negatives (starting new tracks for people that were missed by the camera-only tracker).

Fast Plane Extraction in Organized Point Clouds Using Agglomerative Hierarchical Clustering

Citation: Feng, C., Taguchi, Y., Kamat, V., "Fast Plane Extraction in Organized Point Clouds Using Agglomerative Hierarchical Clustering", *IEEE International Conference on Robotics and Automation (ICRA),* DOI: 10.1109/ICRA.2014.6907776, May 2014, pp. 6218-6225.
Contacts: Yuichi Taguchi

We present a novel algorithm for reliably detecting multiple planes in real time in organized point clouds obtained from devices such as Kinect sensors. By uniformly dividing such a point cloud into non-overlapping groups of points in the image space, we first construct a graph whose node and edge represent a group of points and their neighborhood respectively. We then perform an agglomerative hierarchical clustering on this graph to systematically merge nodes belonging to the same plane until the plane fitting mean squared error exceeds a threshold. Finally we refine the extracted planes using pixel-wise region growing. Our experiments demonstrate that the proposed algorithm can reliably detect all major planes in the scene at a frame rate of more than 35Hz for 640x480 point clouds, which to the best of our knowledge is much faster than state-of-the-art algorithms.

Mechatronics

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, thermofluid system dynamics, laser processing and sensing, 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.

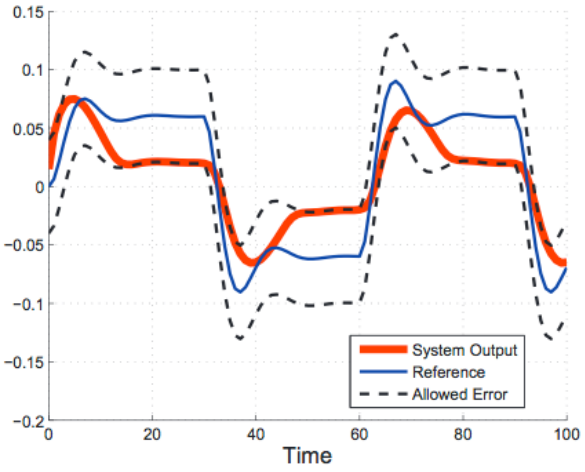
Automatic control systems take real-time measurements of a system under control, process the information with a control algorithm, and apply the results of the calculation back to the system under control via actuators. Feedback is the central concept. MERL's research focuses on development of new control 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 control and nonlinear state and parameter estimation.

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 thermofluid systems dynamics, 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

Constrained Tracking with Guaranteed Error Bounds

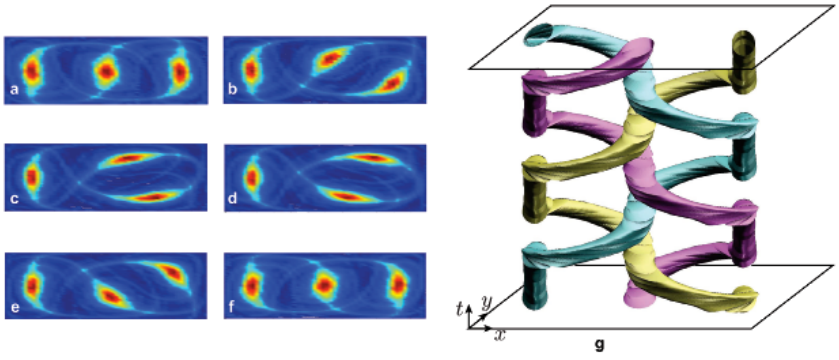
Citation: Di Cairano, S.; Borrelli, F., "Constrained Tracking with Guaranteed Error Bounds", *IEEE Conference on Decision and Control (CDC)*, DOI: 10.1109/CDC. 2013.6760469, ISSN: 0743-1548,pp. 3800-3805, December 2013
Contacts: Stefano Di Cairano



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.

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

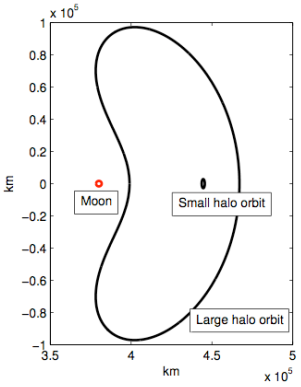


In certain two-dimensional time-dependent flows, the braiding of periodic orbits provides a way to analyze chaos in the system through application of the Thurston-Nielsen classification theorem (TNCT). We expand upon earlier work that introduced the application of the TNCT to braiding of almost-cyclic 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.

Station-keeping and Momentum-management on Halo Orbits Around L2: Linear-quadratic Feedback and Model Predictive Control Approaches

Citation: Kalabic, U., Weiss, A., Di Cairano, S., Kolmanovsky, I.V., "Station-keeping and momentum-management on halo orbits around L2: Linear-quadratic feedback and model predictive control approaches", *AAS/AIAA Space Flight Mechanics Meeting,* January 2015.
Contacts: Avishai Weiss, Stefano Di Cairano

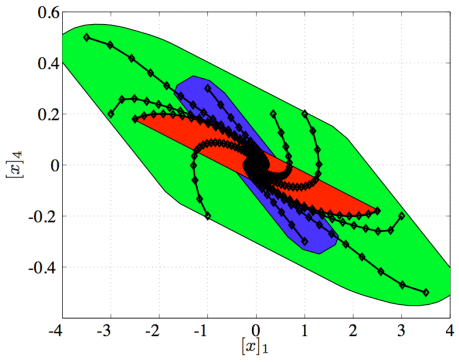
The control of station-keeping and momentum-management is considered while tracking a halo orbit centered at the second Earth-Moon Lagrangian point. Multiple schemes based on linear-quadratic feedback control and model predictive control (MPC) are considered and it is shown that the method based on periodic MPC performs best for position tracking. The scheme is then extended to incorporate attitude control requirements and numerical simulations are presented demonstrating that the scheme is able to achieve simultaneous tracking of a halo orbit and dumping of momentum while enforcing tight constraints on pointing error.



Coordinating Controllers for Constrained Linear Systems by Virtual State Governors

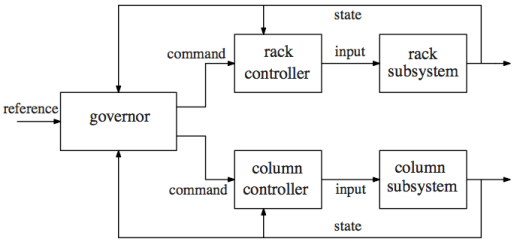
Citation: Di Cairano, S., Kolmanovsky, I.V., "Coordinating Controllers for Constrained Linear Systems by Virtual State Governors", *IEEE Transactions on Automatic Control,* DOI: 10.2209/TAC.2014.2386919, ISSN: 0018-9286, Vol. PP, No. 99, pp. 1, December 2014.
Contacts: Stefano Di Cairano

Constrained control is often applied to systems with redundant actuation. Often, the usage of a specific group of actuators is to be minimized because of its operating cost and/or undesired side-effects, and, sometimes, controllers for each single actuator may have been previously designed. Thus, for cost or organizational considerations, redesigning the entire control strategy may be impractical. Instead, a coordination scheme for regulating the interaction between the existing controllers while enforcing constraints and minimizing the usage of specific actuators can be developed. We propose a coordination strategy for the case when two groups of actuators, each with a non-modifiable state-feedback controller, are available. By using the maximum constraint admissible set for each controller in closed-loop with the plant, the coordination scheme modulates the action of the assigned controllers and minimizes the usage of the expensive actuators. The proposed control strategy enforces constraints, stabilizes the system, and uses the expensive actuators for finite time and only to avoid constraint violation.



Governor-based Control for Rack-Wheel Coordination in Mechanically Decoupled Steering Systems

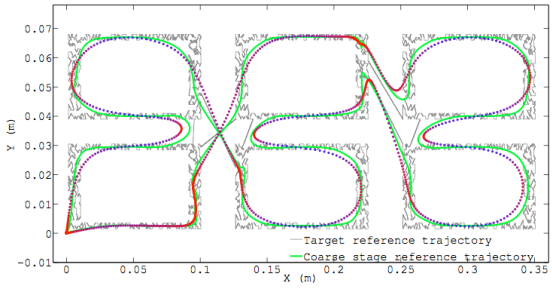
Citation: Zafeiropoulos, S., Di Cairano, S., "Governor-based Control for Rack-wheel Coordination in Mechanically Decoupled Steering Systems", *IEEE Conference on Decision and Control (CDC),* DOI: 10.1109/CDC.2014.7040025, ISBN: 978-1-4799-7746-8, December 2014, pp. 4089-4094.
Contacts: Stefano Di Cairano



A mechanically decoupled steering system enables autonomous or semi-autonomous vehicle steering by independently actuating the vehicle wheels and the steering wheel. In semi-autonomous operation the steering system should be controlled such that the vehicle wheel angles track a reference signal provided by the trajectory planner rapidly and safely, while guaranteeing that a certain alignment is maintained between the steering wheel and the vehicle wheels to avoid loss of driver feel. We develop a controller for a mechanically decoupled steering system that can achieve this by coordinating the steering column and the steering rack actuators, while enforcing constraints on the motion of the vehicle wheels, on the interaction between the steering wheel with the driver, and on the relative motion between steering wheel and vehicle wheels.

Coordinated Control of a Dual-Stage Positioning System Using Constrained Model Predictive Control

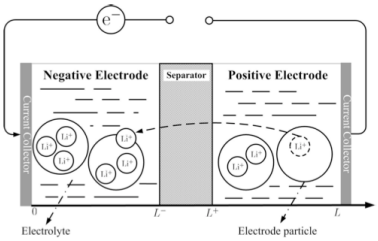
Citation: Haghighat, S., Di Cairano, S., Konobrytskyi, D., Bortoff, S.A., "Coordinated Control of a Dual-Stage Positioning System Using Constrained Model Predictive Control", *ASME Dynamic Systems and Control Conference*, DOI: 10.1115/DSCC2014-6114, ISBN: 978-0-7918-4618-6, October 2014, vol. 1.
Contacts: Stefano Di Cairano, Scott Bortoff



Dual-stage positioning systems have been widely used in factory automation, robotic manipulators, high-density data storage systems, and manufacturing systems. Trajectory generation and control of dual-stage positioning systems is of great importance and is made complicated by the presence of physical and operational constraints. In this work, we describe how to generate feasible reference trajectories for a dual-stage positioning system consisting of a fine stage and a coarse stage, and how to use them in a model predictive control algorithm for which recursive feasibility is guaranteed. The reference generation algorithm is guaranteed to generate trajectories that satisfy all the constraints for the fine and coarse stages. We also describe a constrained model predictive control algorithm used to control the coarse stage. The simulation results of applying the developed methodology to track a pre-determined pattern is presented.

Adaptive Estimation of the State of Charge for Lithium-Ion Batteries: Nonlinear Geometric Observer Approach

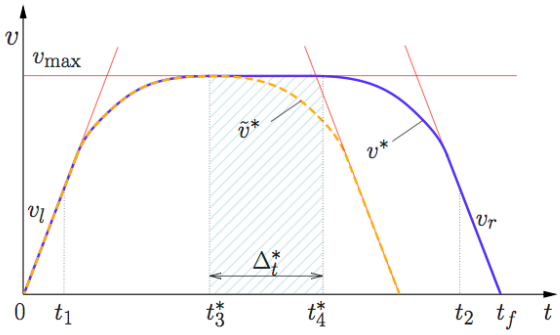
Citation: Wang, Y., Fang, H., Sahinoglu, Z., Wada, T., Hara, S., "Adaptive Estimation of the State of Charge for Lithium-Ion Batteries: Nonlinear Geometric Observer Approach", *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/TCST.2014.2356503, ISSN: 1063-6536, Vol. PP, No. 99, Sept 2014.
Contacts: Yebin Wang, Zafer Sahinoglu



This paper considers the state of charge (SoC) and parameter estimation of lithium-ion batteries. Different from various prior arts, where estimation is based on local linearization of a nonlinear battery model, nonlinear geometric observer approach is followed to design adaptive observers for the SoC and parameter estimation based on nonlinear battery models. 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.

A Real-Time Energy-Optimal Trajectory Generation Method for a Servomotor System

Citation: Wang, Y, Zhao, Y., Bortoff, S.A., Ueda, K., "A Real-Time Energy-Optimal Trajectory Generation Method for a Servomotor System", *IEEE Transactions on Industrial Electronics*, DOI: 10.1109/TIE.2014.2360077, ISSN: 0278-0046, Vol. 62, No. 2, pp. 1175-1188, September 2014
Contacts: Yebin Wang, Scott A. Bortoff



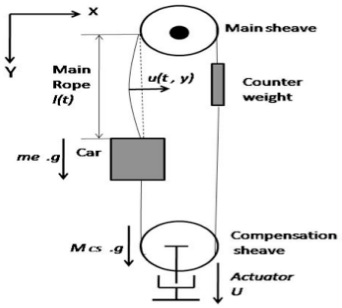
This paper considers real-time energy-optimal trajectory generation for a servomotor system, which performs a single-axis point-to-point positioning task for a fixed time interval. The servomotor system is subject to acceleration and speed constraints. The trajectory generation is formulated as a linear constrained optimal control problem (LCOCP), and the Pontryaginas Maximum Principle is applied to derive necessary optimality conditions. Instead of solving multi-point boundary value problems directly, this paper proposes a novel real-time algorithm based on two realizations: solving the LCOCP is equivalent to determine an optimal time interval of the speed constrained arc and solve a specific acceleration constrained optimal control problem (ACOCP); solving an ACOCP is equivalent to determine optimal switch times of acceleration constrained arcs and solve a specific two-point boundary value problem (TBVP). The proposed algorithm constructs sequences of time intervals, ACOCPs, switch times, and TBVPs, such that all sequences converge to their counterparts of an optimal solution of the LCOCP.

Lyapunov-Based Control of the Sway Dynamics for Elevator Ropes

Citation: Benosman, M., "Lyapunov-based Control of the Sway Dynamics for Elevator Ropes", *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/TCST.2013.2294094, ISSN: 1063-6536, Vol. 22,No. 5, pp. 1855-1863, September 2014.

Contacts: Mouhacine Benosman

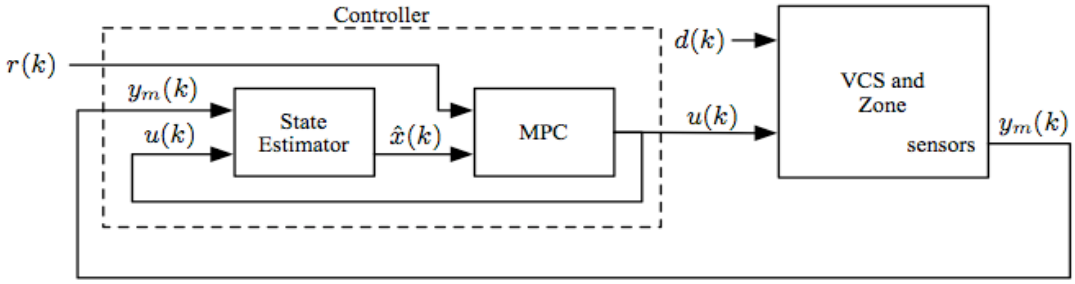
In this brief, we study the problem of rope sway dynamics control for elevator systems. We choose to actuate the system with a force actuator pulling on the compensation sheave. Under these conditions, we formulate this problem as a bilinear control problem and propose several nonlinear controllers based on Lyapunov theory to stabilize the rope sway dynamics, for different elevator operation conditions. We present a stability analysis of the proposed controllers, and illustrate their performance via numerical tests.



Model Predictive Control of Vapor Compression Systems

Citation: Jain, N., Burns, D.J., Di Cairano, S., Laughman, C.R., Bortoff, S.A., "Model Predictive Control of Vapor Compression Systems", *International Refrigeration and Air Conditioning Conference at Purdue*, July 2014,pp. 1-10.

Contacts: Daniel J. Burns, Stefano Di Cairano, Christopher Laughman, Scott A. Bortoff

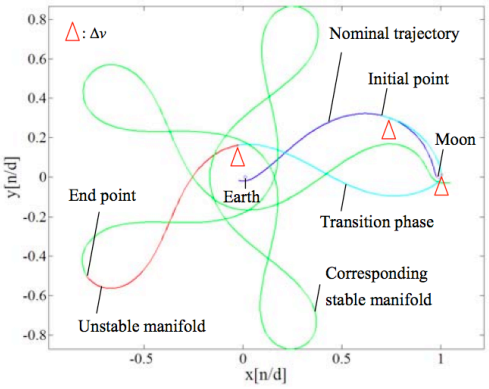


Model Predictive Control (MPC) of vapor compression systems (VCSs) offers several advantages over conventional control methods (such as multivariable process control with selector logic) in terms of 1) the resulting closed-loop performance and 2) the control engineering design process. VCSs are multivariable systems and feature constraints on system variables and actuators that must be enforced during steady-state and transient operation. We present the design and validation of an MPC for a split ductless VCS. The design regulates room temperature with zero steady state error for unknown changes in the thermal load and enforces constraints on system variables such as compressor discharge temperature and actuator ranges and rates. We show how the MPC design can evolve during the engineering process by adding and modifying constraints and process variables. The design methodology provides guarantees in terms of closed loop stability and convergence. In contrast to other published results on MPC for VCSs, our design makes use of only available temperature measurements and does not require pressure or mass flow measurements which are typically not available in production VCSs.

Design of Low Fuel Trajectory in Interior Realm as a Backup Trajectory for Lunar Exploration

Citation: Sato, Y., Grover, P., Yoshikawa, S., "Design of Low Fuel Trajectory in Interior Realm as a Backup Trajectory for Lunar Exploration", *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerosplace Technology Japan*, DOI: 10.2322/tastj.12.Pd_47, Vol. 12, pp. 47-52, June 2014.

Contacts: Piyush Grover

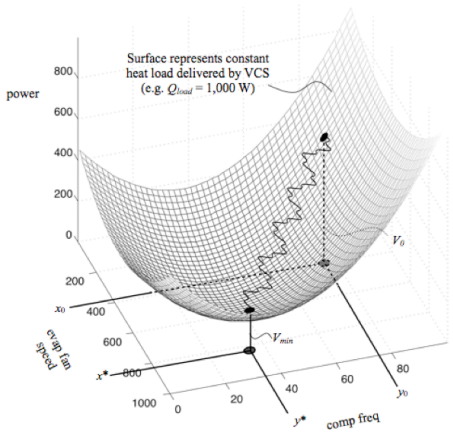


In case of a failure on a Hohmann-base translunar trajectory, a reconfiguration of the trajectory that utilizes the three body dynamics of the interior realm of Earth-moon system is proposed. The stable and unstable manifold of a periodic orbit around the L1 point extended toward the Earth side have homoclinic intersections. In the proposed method, after detection of a failure on the nominal trajectory, the trajectory is modified by small maneuvers so that the spacecraft can be kicked back by the moon and transferred to the unstable manifold. Then the spacecraft is returned back to the moon side through the intersection with the corresponding stable manifold on the Earth side. The periodic orbit is again used as a parking orbit so that the amount of delta-v at the moon orbit insertion can be reduced. Since the required amounts of delta-v at each individual maneuver are small throughout the reconfigured trajectory, it can serve as a solution for a backup trajectory in case of a main engine failure.

A Comparison of Extremum Seeking Algorithms Applied to Vapor Compression System Optimization

Citation: Guay, M., Burns, D.J., "A Comparison of Extremum Seeking Algorithms Applied to Vapor Compression System Optimization", *American Control Conference (ACC)*,DOI: 10.1109/ACC.2014.6859288, ISSN: 0743-1619, ISBN: 978-1-4799-3272-6, pp. 1076-1081, June 2014.

Contacts: Daniel J. Burns



In recent years, a number of extremum seeking algorithms have been proposed. While each approach aims to estimate the gradient of a performance metric in realtime and steer inputs to values that optimize the metric, the way in which each method accomplishes this goal can have practical implications that depend on the application. In this paper, we compare the performance of traditional perturbation-based extremum seeking to time-varying extremum seeking in the context of optimizing the energy efficiency of a vapor compression system. In order to benchmark these algorithms, we simulate their performance using a moving-boundary model of a vapor compression machine that has been tuned and calibrated to data gathered from a multi-split style room air conditioner operating in cooling mode.

Projection-free Parallel Quadratic Programming for Linear Model Predictive Control

Citation: Di Cairano, S., Brand, M., Bortoff, S., "Projection-free Parallel Quadratic Programming for Linear Model predictive Control", *International Journal of Control*, July 2013.

Contacts: Stefano Di Cairano, Matthew E. Brand, Scott A. Bortoff

Solver	Avg[ms]	Min[ms]	Max[ms]
PQP-M:	**0.588**	0.304	**2.264**
GPAD-M:	3.450	**0.252**	18.733
QPROG:	1.545	1.348	2.557
QPACT:	0.454	0.321	0.920
QPOAS:	0.210	0.155	0.376
NAG:	0.610	0.410	1.115
PQPMEX:	0.068	0.041	0.154
PQPMPC:	**0.022**	**0.018**	**0.049**

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.

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.

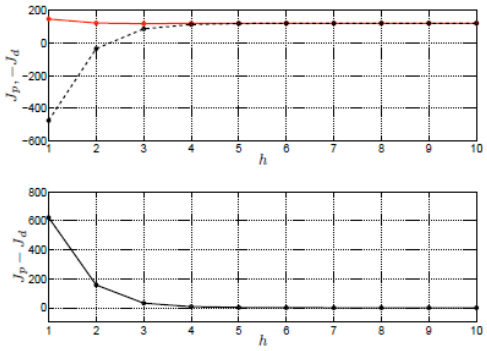
Most of the group's work revolves around graph-based optimizations and inference, where the graph is a representation of the problem constraints and a probability distribution over possible solutions. Through formal analysis we identify tractable estimation or approximation schemes. This meshes with 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



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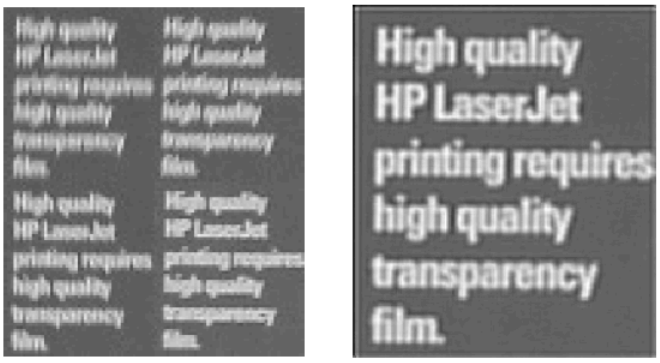
Parallel Quadratic Programming for Image Processing

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

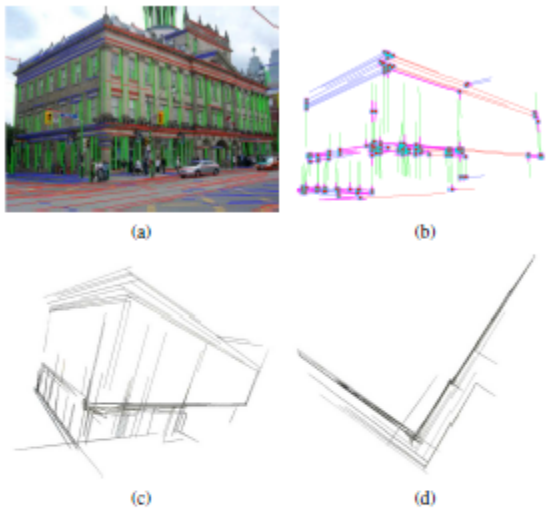
Many image processing and computer vision problems can be solved as quadratic programs in the non-negative cone. This paper develops a provably convergent multiplicative update that has a simple form and is amenable to fine-grained data parallelism. Classic algorithms for deblurring, matrix factorization, 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.