Mitsubishi Electric Research Laboratories (MERL)

Annual Report

April 2017 through March 2018

TR2018-00

(Published July 2018)

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

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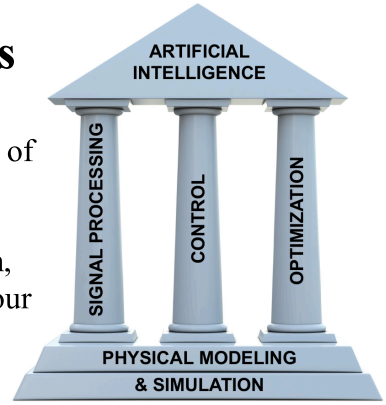
Mitsubishi Electric Research Laboratories



Mitsubishi Electric Research Laboratories (MERL) is the US subsidiary of the corporate research and development organization of Mitsubishi Electric Corporation. MERL conducts application-motivated basic research and advanced development in: Physical Modelling & Simulation, Signal Processing, Control, Optimization, and Artificial Intelligence. The main body of this report presents our recent research in these areas.

MERL's mission—our assignment from Mitsubishi Electric:

- Generating new technology and intellectual property in areas of importance to Mitsubishi Electric.
- Impacting Mitsubishi Electric's business significantly: 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 a premiere research laboratory, 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:

- Recruiting the highest-quality researchers and developing them into leaders in their fields, encouraging everyone to be a principal investigator and pursue their passions.
- Fostering interdisciplinary teamwork inside MERL with our colleagues at Mitsubishi Electric, and with interns and universities.
- Participating in the world research community, publishing our work while maintaining the confidentiality of business information.
- Combining nimble bottom-up research direction setting with stable long-term support from our large parent organization.
- Enabling researchers to both extend the frontier of science and make real products happen through the large and capable engineering workforce of Mitsubishi Electric.
- Providing excellent benefits and a flexible work environment.

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 seven 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. Akira Ishihara (EVP & CFO) —— Finance & Liaisons
  - Elizabeth Phillips —— HR & Administration
  - Dr. Anthony Vetro, IEEE Fellow (VP & Director) —— Patents
    - CV: Computer Vision Group - Dr. Alan Sullivan
    - DA: Data Analytics Group - Dr. Daniel Nikovski
    - SA: Speech & Audio Group - Dr. Anthony Vetro, IEEE Fellow
  - Dr. Jinyun Zhang, IEEE Fellow (VP & Director)
    - SP: Signal Processing Group - Dr. Phil Orlik
    - CD: Control and Dynamical Systems Group - Dr. Jay Thornton
    - MP: Multi-Physical Systems & Devices Group - Dr. Jinyun Zhang
  - AL: Algorithm Group - Dr. Joseph Katz, (Advisor) IEEE & OSA Fellow

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 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. At MERL, his research centered on multi-user interactive environments for work, learning, and play. In 1999, he became CEO of MERL as a whole.

Akira Ishihara *Ph.D., University of Osaka, 2010*
Executive Vice President & CFO

Akira joined Mitsubishi Electric in 1993 and did research on software platforms for computer supported cooperative work, supervisory control and data acquisition systems, and manufacturing execution systems. He has also done research on software engineering technology and is interested in applying it to designing large-scale industrial systems. Before joining MERL in 2018, he was the manager of the Strategic Planning Department in Mitsubishi Electric's Advanced Technology Center.

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 U. (now the NYU), 2001*
Vice President & Director, IEEE Fellow

Anthony joined MERL in 1996 and conducted 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 has also served in various leadership roles for conferences, technical committees and editorial boards. He joined MERL's top management in 2014.

Elizabeth Phillips *B.A., University of Massachusetts Amherst, 1988*
Manager, Human Resources & Administration

Elizabeth has over 25 years of human resources experience. For 12 years before joining MERL in 2014 she was the principal of a boutique human resources consulting firm in New England, which supported small to mid-size companies with all aspects of their employee related needs. Engagements included: on-site HR leadership, development of talent management programs, management of total rewards programs, facilitation of employee development programs, and HR compliance and administration.

Joseph Katz *Ph.D., California Institute of Technology, 1981*
Advisor, 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.

Mitsubishi Electric

One of the world's largest companies, Mitsubishi Electric Corporation has $41 billion in annual sales, $2.9 billion in operating profits (in the year ending in March 2018) and more than 139,000 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
- **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**
  Air Conditioners, Home Appliances
- **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 separated 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. Andrew Knyazev - Fellow, Society for Industrial and Applied Mathematics
Dr. Keisuke Kojima - Fellow, Optical Society of America
Dr. Huifang Sun - Fellow, Institute of Electrical and Electronic Engineers
Dr. Anthony Vetro - Fellow, Institute of Electrical and Electronic Engineers
Dr. Jin Zhang - Fellow, Institute of Electrical and Electronic Engineers

Awards and Major Events

MERL's speech researchers achieved a top ranking on an end-to-end dialog system submitted to the 6th edition of the Dialog System Technology Challenge (DSTC6).

The paper Zhu, Y.; Imamura, M.; Nikovski, D.N.; Keogh, E., "Matrix Profile VII: Time Series Chains: A New Primitive for Time Series Data Mining", won the Best Student Paper Award at the 2017 International Conference on Data Mining.

MERL is among the top 10 organizations in Massachusetts in terms of patent filings in 2010-2015 based on a recent report by JLL . This is especially notable since MERL is by far the smallest organization in that group.

It is 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: 11 in the American Control Conference (ACC), 7 in the IEEE International Conference on Communications (ICC) 6 in the IEEE Conference on Control Technology and Applications and 6 in the Optical Fiber Communication Conference (OFC). 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.

Heejin Ahn *Ph.D., Massachusetts Institute of Technology, 2018*
Visiting Research Scientist

Prior to joining MERL, Heejin worked on control and optimization at MIT, with a minor in mathematical analysis. Her dissertation was about safety verification and control for cooperative vehicles at road intersections. Her current research interests include the analysis and control of cyber-physical systems.

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

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.

Mouhacine Benosman *Ph.D., Ecole Centrale de Nantes, 2002*
Senior Principal Research Scientist

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*
Research Scientist

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.

Daniel Birch
Visiting Research Scientist

Daniel earned his Ph.D. and did postdoctoral work in oceanography, where he studied mathematical models for plankton distributions and mixing in the ocean. After taking a few years to teach high school physics, Daniel returned to research and currently works on developing innovative lighting technologies at MERL.

Scott A. Bortoff *Ph.D., University of Illinois Urbana-Champaign, 1992*
Strategic Project Leader, Distinguished Research Scientist

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 Research Scientist, Team Leader

Petros was a Postdoctoral associate at Rice 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.

Daniel J. Burns *Ph.D., Massachusetts Institute of Technology, 2010*
Senior Principal Research Scientist

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.

Esra Cansizoglu *Ph.D., Northeastern University, 2015*
Research Scientist

Prior to joining MERL, Esra worked on biomedical image processing and machine learning at the Cognitive Systems Laboratory, Northeastern University. Her dissertation was about retinal vasculature extraction, disease classification and analysis of inter-expert variability. Her current research interests include 3D reconstruction and multi-view geometry.

Ankush Chakrabarty *Ph.D., Purdue University, 2016*
Visiting Research Scientist

At Purdue, Ankush's research focused on developing scalable, data-driven methods for simplifying computationally intensive operations encountered in controlling and observing complex, nonlinear systems. Prior to joining MERL, Ankush was a postdoctoral Fellow at Harvard where he designed embedded model predictive controllers and deep learning-assisted control strategies for treating people with type 1 diabetes.

Anoop Cherian *Ph.D., University of Minnesota, 2013*
Research Scientist

Anoop was a postdoctoral researcher in the LEAR group at Inria 2012-2015 where his research was on the estimation and tracking of human poses in videos. 2015-2017, he was a Research Fellow at the Australian National University, where he worked on recognizing human activities in video. Currently, his research focus is on modeling the semantics of video data.

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

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.

Radu Corcodel *Ph.D., University of Connecticut, 2017*
Visiting Research Scientist

Radu's PhD focused on workspace analysis and motion synthesis for arbitrary kinematic chains, with particular emphasis on robotic 3D printing and Fusion Deposition Modeling. Currently his research focuses on motion planning and workspace analysis for over-actuated kinematic linkages and collaborative robots.

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

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

Marissa Deegan *B.A., Saint Michael's College, 2009*
HR Generalist/ Administrator

Marissa joined MERL in 2015. She has experience in as coordinator of customer service and administration departments. Previously, she worked as a Coordinator of Customer Service and Administration in a soccer company for children. Her interests are in HR and is pursuing an MBA.

Stefano Di Cairano *Ph.D., University of Siena, 2008*
Senior Principal Research Scientist, Optimization 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.

Chen Feng *Ph.D., University of Michigan, 2015*
Research Scientist

Chen's Ph.D. research was on computer vision and robotics for construction automation, including camera pose estimation and 3D scene understanding. At MERL, he has worked on SLAM using points and planes, and invented a fast plane extraction algorithm. His research interests include computer vision, photogrammetry, robotics, machine learning, and augmented reality.

Abraham M. Goldsmith *M.S., Worcester Polytechnic Institute, 2008*
Principal Research Scientist

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 of electro-mechanical systems. In addition, Abraham provides electrical and mechanical engineering support to the entire laboratory.

Piyush Grover *Ph.D., Virginia Polytechnic Institute & State Univ., 2010*
Principal Research Scientist

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 Research Scientist

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 Research Scientist

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.

Chiori Hori *Ph.D., Tokyo Institute of Technology, 2002*
Principal Research Scientist

Prior to joining MERL in 2015, Chiori spent 8 years at Japan's National Institute of Information and Communication Technology (NICT), rising to research manager of the Spoken Language Communication Lab. Chiori's work has focused on speech summarization/translation, spoken dialog technology, and standardization of speech interface communication protocols.

Takaaki Hori *Ph.D., Yamagata University, 1999*
Principal Research Scientist

Before joining MERL in 2015, Takaaki spent 15 years doing research on speech and language technology at Nippon Telegraph, and Telephone in Japan. His work includes speech recognition algorithms using weighted finite-state transducers (WFSTs), efficient search algorithms for spoken document retrieval, spoken language understanding, and automatic meeting analysis.

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.

Devesh Jha *Ph.D., Pennsylvania State University, 2016*
Research Scientist

Devesh's PhD Thesis was on decision & control of autonomous systems. He also got a Master's degree in Mathematics from Penn State. His research interests are in the areas of Machine Learning, Time Series Analytics and Robotics. He was a recipient of the best student paper award at the 1st ACM SIGKDD workshop on Machine Learning for Prognostics and Health Management at KDD 2016, San Francisco.

Michael J. Jones *Ph.D., Massachusetts Institute of Technology, 1997*
Senior Principal Research Scientist

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

Uros Kalabic *Ph.D., University of Michigan, 2015*
Research Scientist

Uros works on advancements in the theory of predictive control and constrained control, as well as its applications to the control of automotive and aerospace systems. His dissertation dealt with theoretical developments and practical applications of reference governors. Prior to joining MERL, Uros interned at MERL and at Ford Motor Company.

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

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 Research Scientist, SIAM Fellow

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 sciences, optimal control, material sciences, and numerical simulation of complex phenomena.

Toshiaki Koike-Akino *Ph.D., Kyoto University, 2005*
Senior Principal Research Scientist

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 Research Scientist

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.

Emil Laftchiev *Ph.D., Pennsylvania State University, 2015*
Research Scientist

Emil's research interests are in the identification of efficient storage methods using dimension reducing data features. The purpose of this research is to enable rapid continuous localization within the data. Prior to joining MERL Emil served as a Distinguished Teaching Fellow for the College of Engineering at the Pennsylvania State University.

Christopher Laughman *Ph.D., Massachusetts Institute Technology, 2008*
Senior Principal Research Scientist, Team Leader

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*
Senior Principal Research Scientist, Team Leader

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.

Teng-Yok Lee *Ph.D., Ohio State University, 2011*
Research Scientist

Teng-Yok's research interests are visual (computer graphics, visualization, and image processing) and computational (GPU, high performance and cloud computing). His PhD studies were about the visualization of scientific results, especially time-varying and Computational Fluid Dynamics (CFD) data.

Chungwei Lin *Ph.D., Columbia University, 2008*
Research Scientist

Before joining MERL, Chungwei was a postdoctoral researcher in the Physics Department of the University of Texas at Austin. His particular interest is the use of doping/interface to control optical, thermal, and transport properties. He has worked on the theory of self-assembly, configuration interaction quantum impurity solvers, and photoemission spectroscopy.

Dehong Liu *Ph.D., Tsinghua University, 2002*
Senior Principal Research Scientist

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.

Rui Ma *Ph.D., University of Kassel, 2009,*
Senior Principal Research Scientist

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

Hassan Mansour, *Ph.D. University of British Columbia, 2009*
Principal Research Scientist

Hassan's research interests are in 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. Subsequent work developed adaptive sparse recovery algorithms for correlated signals from compressive measurements.

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

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.

James McAleenan *J.D., Hamline University Law School, 1999*
Patent Counsel

Jim is a registered patent attorney and former U.S. Patent Examiner with more than 16 years of experience in patent and Intellectual Property law. Jim has held in-house legal roles at significant U.S. and multinational companies, having served as Senior Patent Counsel and Senior Intellectual Property Attorney.

Kathleen McCarthy *B.A., Boston College, 1992*
Controller

Kathleen has worked for over 30 years in the Accounting field with experience in general accounting, payroll and property management. Prior to joining MERL in 1993, she worked in manufacturing, financial and service industries.

Kerry McKeon *B.A., Saint Michael's College, 2010*
Lab Administrator

Kerry has her BA in Psychology and is currently pursuing a masters in Licensed Mental Health Counseling. Kerry has experience in various fields working as a service coordinator and developmental specialist with families and children. Her interests are in human development research, specifically on the impact of societal changes on development throughout the years.

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

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* (Dominican Republic)*, 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.

Saleh Nabi *Ph.D., University of Alberta, 2014*
Adjunct Research Scientist

Saleh's research interests are analytical, numerical and similitude experimental modeling of fluid flow and heat transfer in complex systems. His ambition is to derive reduced order models for turbulent buoyancy-driven flows in confined regions to reduce the simulation run time by several orders of magnitude. Saleh’s doctoral research mainly focused on environmental and architectural fluid mechanics applied to airflow modeling.

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*
Principal Research Scientist

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 Research Scientist, 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 Research Scientist

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.

Kristin Peterson *B.S., Towson University, 2007*
Patent Paralegal

Kristin joined MERL in 2012 as a Patent assistant. Prior to working at MERL she attended Boston University's Paralegal program to support a career change. She previously held a position in hospital finance and was a Realtor in the Maryland metropolitan area. She has a Bachelor of Science degree in Psychology.

Hongtao Qiao *Ph.D., University of Maryland, 2014*
Research Scientist

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.

Rien Quirynen *Ph.D., KU Leuven and University of Freiburg, 2017*
Research Scientist

Rien's research interests are in model predictive control and moving horizon estimation, numerical algorithms for (nonlinear) dynamic optimization and real-time control applications. His doctoral research was focused on numerical simulation methods with efficient sensitivity propagation for real-time optimal control algorithms.

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

Arvind's research focuses on optimization algorithms large-scale 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, and energy systems.

Diego Romeres *Ph.D., University of Padova, 2017*
Research Scientist

Diego's research interests are in machine learning, system identification and robotic applications. At MERL he is currently working on applying nonparametric machine learning techniques for the control of robotic platforms. His Ph.D. thesis is about the combination of nonparametric data-driven models and physics-based models in gaussian processes for robot dynamics learning.

Alan Sullivan *Ph.D., University of California at Berkeley, 1993*
Computer Vision Group Manager

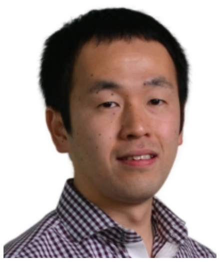
First at U.C. Berkeley, then at Lawrence Livermore National Laboratory, Alan studied interactions between ultra-high intensity femtosecond lasers and plasmas. Prior to joining MERL in 2007, he worked at a series of start-ups where he developed a novel volumetric 3D display technology. At MERL His research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

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

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 with more than 20 years' experience in technical consulting, product development and research on electrical transmission and distribution system planning, analysis, 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*
Senior Principal Research Scientist

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 Research Scientist, 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*
Mechatronics 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 Research Scientist

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.

Hironori Tsukamoto *Ph.D., Tokyo Institute of Technology, 1999*
Patent Agent

Tsukamoto worked as a research scientist in the area of silicon and compound semiconductor materials/devices at Sony Research Center and Yale University for more than 15 years. Prior to joining MERL, he worked at a Japanese Patent Firm to support US patent practice of Japanese client companies for more than 5 years.

Jeroen van Baar *Ph.D., ETH Zurich, 2013*
Senior Principal Research Scientist

Jeroen came to MERL in 1997 as an 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*
Senior Patent Counsel

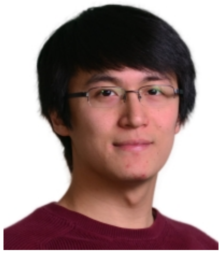
Gene graduated cum laude with distinction in Intellectual Property law. In addition, he holds advanced degrees in Mechanical Engineering and Computer Science. He is a member of Massachusetts Bar and has been a licensed patent practitioner since 2003.

Bingnan Wang *Ph.D., Iowa State University 2009*
Principal Research Scientist

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.

Pu Wang *Ph.D., Stevens Institute of Technology, 2011*
Principal Research Scientist

Before coming to MERL, Pu was a Research Scientist in the Mathematics and Modeling Department of Schlumberger-Doll Research, contributing to development of logging-while-drilling Acoustic/NMR products. His current research interests include statistical signal processing, Bayesian inference, sparse signal recovery, and their applications to sensing, wireless communications, and networks.



Ye Wang *Ph.D., Boston University, 2011*
Principal Research Scientist

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*
Senior Principal Research Scientist

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

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

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.

Gordon Wichern *Ph.D., Arizona State University, 2010*
Principal Research Scientist

Gordon's research interests are at the intersection of signal processing and machine learning applied to speech, music, and environmental sounds. Prior to joining MERL, Gordon worked at iZotope inc. developing audio signal processing software, and at MIT Lincoln Laboratory where he worked in radar target tracking.

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

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

Victoria Wong *B.S. Bentley College, 2008*
Principal Staff Accountant

Victoria has over 10 years' experience primarily focusing on accounts payable and payroll. She joined MERL in June, 2008. Prior to joining MERL, she was an intern with Federal Reserve Bank of Boston and EF Education. Her B.S. degree is in Accounting Information Systems.

William S. Yerazunis *Ph.D., Rensselaer Polytechnic Institute, 1987*
Senior Principal Research Scientist

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, and was voted one of the 50 most important people in computer network security by Network World magazine.

Jing Zhang *Ph.D., Boston University, 2017*
Research Scientist

Jing's PhD dissertation was on detection and optimization problems with applications in transportation systems. His research interests include anomaly detection, optimization, machine learning, and time series analysis. He was a recipient of the Boston Area Research Initiative (BARI) Research Seed Grant Award (Spring 2017).

Ziming Zhang *Ph.D., Oxford Brookes University, 2013*
Research Scientist

Before joining MERL he was a research assistant professor at Boston University, MA. His research interest lies in computer vision and machine learning, including object recognition and detection, zero-shot learning, optimization, etc. His works have appeared in TPAMI, CVPR, ICCV, ECCV, ACM MM and NIPS.

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.

Raghunathan, A.U.; Biegler, L.T., **“LDL^T Direction in interior point method for semidefinite programming”**, *SIAM Journal on Optimization*, DOI: 10.1137/16M1105888, Vol. 28, No. 1, pp. 693-734, March 2018 (TR2018-037)

Wang, Y.; Utsunomiya, K., **“From acceleration-based semi-active vibration reduction control to functional observer design”**, *Automatisierungstechnik*, DOI: 10.1515/auto-2017-0064, Vol. 66, No. 3, March 2018 (TR2018-035)

Teng, M.; Kojima, K.; Koike-Akino, T.; Wang, B.; Lin, C.; Parsons, K., **“Broadband SOI mode order converter based on topology optimization”**, *Optical Fiber Communication Conference and Exposition (OFC)*, DOI: 10.1364/OFC.2018.Th2A.8, March 2018 (TR2018-019)

Koike-Akino, T.; Cao, C.; Wang, Y.; Kojima, K.; Millar, D.S.; Parsons, K., **“Irregular Polar Turbo Product Coding for High-Throughput Optical Interface”**, *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, DOI: 10.1364/OFC.2018.Tu3C.5, March 2018 (TR2018-017)

Kojima, K.; Yoshida, T.; Parsons, K.; Koike-Akino, T.; Millar, D.S.; Matsuda, K., **“Comparison of nonlinearity tolerance of modulation formats for subcarrier modulation”**, *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, DOI: 10.1364/OFC.2018.M2C.4, March 2018 (TR2018-018)

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Millar, D.S.; Fehenberger, T.; Koike-Akino, T.; Kojima, K.; Parsons, K., **“Coded Modulation for Next-Generation Optical Communications”**, *Optical Fiber Communication Conference and Exposition (OFC)*, DOI: 10.1364/OFC.2018.Tu3C.3, March 2018 (TR2018-020)

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Pajovic, M.; Preisig, J.C.; Baggeroer, A.B., **“Analysis of Optimal Diagonal Loading for MPDR-based Spatial Power Estimators in the Snapshot Deficient Regime”**, *IEEE Journal of Oceanic Engineering*, DOI: 10.1109/JOE.2018.2815480, March 2018 (TR2018-031)

Kamilov, U.; Mansour, H.; Wohlberg, B., **“Plug-and-Play FISTA for Solving Nonlinear Imaging Inverse Problems”**, *IEEE Signal Processing Letters*, DOI: 10.1109/LSP.2017.2763583, Vol. 24, No. 12, pp. 1872- 1876, March 2018 (TR2018-029)

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Berntorp, K.; Grover, P., **“Feedback Particle Filter with Data-Driven Gain-Function Approximation”**, *IEEE transactions on aerospace and electronic systems*, DOI: 10.1109/TAES.2018.2807559, February 2018 (TR2018-034)

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Tian, N.; Fang, H.; Wang, Y., **“Three-Dimensional Temperature Field Reconstruction for A Lithium-Ion Battery Pack: A Distributed Kalman Filtering Approach”**, *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/TCST.2017.2779434, pp. 1-8, January 2018 (TR2018-012)

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Sun, H.; Takaguchi, Y.; Nikovski, D.N.; Hashimoto, H., **"Three-Level Co-optimization Model for Generation Scheduling of Integrated Energy and Regulation Market"**, *IEEE Innovative Smart Grid Technologies Conference*, December 2017 (TR2017-158)

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Egashira, H.; Suzuki, J.; Koike-Akino, T.; Nakano, T.; Fukuda, H.; Orlik, P.V., **"Molecular Fountain: A Robustness Enhancement Framework for Diffusive Molecular Communication"**, *IEEE Global Communications Conference (GLOBECOM)*, DOI: 10.1109/GLOCOM.2017.8255064, December 2017 (TR2017-177)

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Gupta, R.; Kalabic, U.; Bloch, A.; Kolmanovsky, I.V., **"Solution to the HJB Equation for LQR-Type Problems on Compact Connected Lie Groups"**, *Automatica*, November 2017 (TR2017-171)

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Liu, C.; Zhou, M.; Wu, J.; Long, C.; Wang, Y., **"Electric Vehicles En-route Charging Navigation Systems: Joint Charging and Routing Optimization"**, *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/TCST.2017.2773520, November 2017 (TR2017-126)

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Shulkind, G.; Pajovic, M.; Orlik, P.V., **"Packet Separation in Random Access Channels Via Approximate Sparse Recovery"**, *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, DOI: 10.1109/GlobalSIP.2017.8309085, November 2017 (TR2017-166)

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Farahmand, A.-M.; Barreto, A.M.S.; Nikovski, D.N., **"Value-Aware Loss Function for Model Learning in Reinforcement Learning"**, *Artificial Intelligence and Statistics (AISTATS)*, Vol. 54, April 2017 (TR2017-049)

Lin, C.; Wang, B.; Teo, K.H.; Bandaru, P.R., **"Application of impedance matching for enhanced transmitted power in a thermophotovoltaic system"**, *Physical Review Applied*, DOI: 10.1103/PhysRevApplied.7.034003, Vol. 7, No. 3, April 2017 (TR2017-047)

Research

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

Computer Vision – 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.

Data Analytics – Learning and optimization algorithms that can be applied to 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, increases reliability, improves energy efficiency, and reduces environmental impact of products.

Speech & Audio – Machine learning for estimation and inference problems in speech and audio processing, including end-to-end speech recognition and enhancement, acoustic modeling and analysis, statistical dialog systems, as well as natural language understanding and adaptive multimodal interfaces.

Signal Processing – Acquisition, representation, and processing of signals with an emphasis on wireless/optical communications and associated devices, computational sensing, radar processing and statistical inference. Application areas include: terrestrial and trans-oceanic optical networks, train and automotive connectivity and electronics, energy storage systems, RF power amplifiers, RF sensing systems for security, infrastructure and building monitoring.

Control & Dynamical Systems – If it moves, we control it: Advanced control algorithms, model predictive control, estimation, nonlinear dynamical systems, system-level dynamic modeling and analysis, mechatronic co-design, thermo-fluid system dynamics, with applications to automotive mechatronics, factory automation, elevators, space systems, motors, trains, and HVAC.

Multi-Physical Systems & Devices – Research on multi-physical modeling & simulations as a basis for producing model-based design for devices, systems and controls to achieve optimized performance with high efficiency. Target applications include HVAC systems, factory automation, robotics, electrical motors, power amplifier devices, superconductors, and nano-particles for future magnetic particle imaging.

Algorithms – Reduced-complexity solutions for optimization problems involving very large numbers of variables and constraints. Bounded-time methods for real-time signal processing, learning and control. Radiative inverse problems. Computational optics. Adaptively-sampled distance fields-based methods in various domains ranging from font rendering to NC milling simulation.

Computer Vision

The research in the Computer Vision group at MERL covers all aspects of extracting information from images, videos and point clouds. For instance, from a picture or video of a scene we can compute features that allow the detection and localization of specific objects. We can track a moving object in video to quantify its trajectory. In some cases, we can modify the image creation process to make subsequent information extraction more effective. For instance, multiple flash exposures can be used to identify an object's edges.

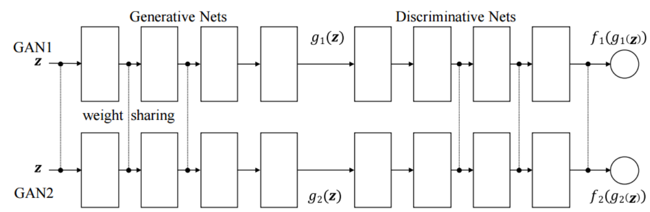
Several of our current projects involve 3D analysis based on 2D images. For example, we have developed algorithms for estimation of object pose so that a robot arm can grasp an object from a cluttered workspace. In another project, we build a 3D model from 2D images that can be used for automatic parking. 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. We process point clouds of data from laser scans of objects and scenes to extract data for map generation, vehicle localization, and object classification.

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 also developed physics-based simulators of 3D puzzles and use reinforcement learning to train a real robot to solve the puzzle. We have 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

Coupled Generative Adversarial Nets

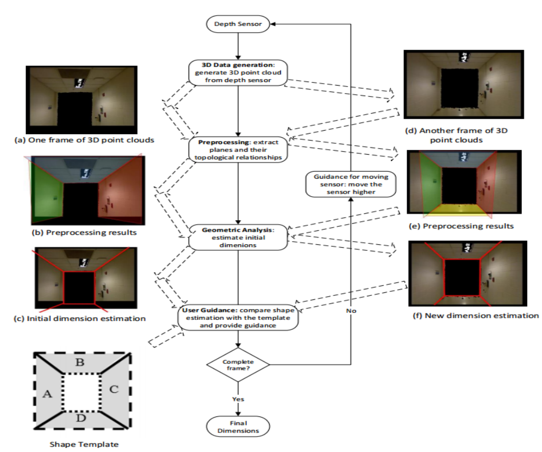
Citation: Liu, M.-Y.; Tuzel, C.O.; Sullivan, A., "Coupled Generative Adversarial Nets", *Advances in Neural Information Processing Systems (NIPS)*, December 5, 2016.
Contacts: Alan Sullivan



We propose the coupled generative adversarial nets (CoGAN) framework for generating pairs of corresponding images in two different domains. The framework consists of a pair of generative adversarial nets, each responsible for generating images in one domain. We show that by enforcing a simple weight-sharing constraint, the CoGAN learns to generate pairs of corresponding images without existence of any pairs of corresponding images in the two domains in the training set. In other words, the CoGAN learns a joint distribution of images in the two domains from images drawn separately from the marginal distributions of the individual domains. This is in contrast to the existing multi-modal generative models, which require corresponding images for training.

User-Guided Dimensional Analysis of Indoor Building Environments from Single Frames of RGB-D Sensors

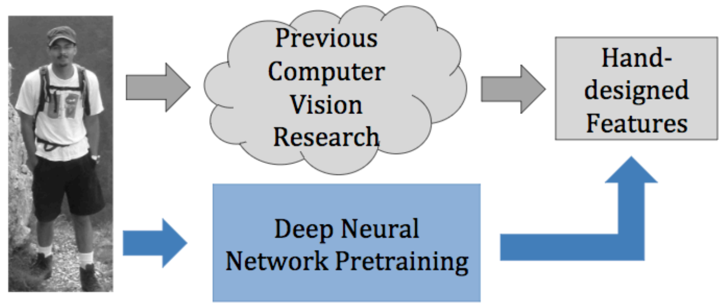
Citation: Xiao, Y.; Feng, C.; Taguchi, Y.; Kamat, V.R., "User-Guided Dimensional Analysis of Indoor Building Environments from Single Frames of RGB-D Sensors", *Journal of Computing in Civil Engineering*, DOI: 10.1061/(ASCE)CP.1943-5487.0000648, November 30, 2016.
Contacts: Chen Feng, Yuichi Taguchi



In many construction, facility management, and inspection tasks, dimensional analysis of geometric features and artifacts is significant for spatial analysis and decision making. Tasks such as as-built geometry modeling and robotic workspace generation need to efficiently interpret critical dimensions of specific objects (e.g., diameter of a pipe, width of an opening) in a potentially cluttered environment based on data gathered from various positions. This paper presents a user-guided dimensional analysis approach to automatically acquire geometric information from a single frame of an RGB-D sensor. An RGB-D sensor is used to capture three-dimensional (3D) point clouds of building environments. Then, by extracting planes and performing geometric analysis, the dimensional information of objects of interest is obtained from a single frame. The user guidance system evaluates the completeness of the acquired data, and provides interactive guidance for moving the sensor to acquire complete data, from which accurate geometric measurements can be obtained.

Unsupervised Network Pretraining via Encoding Human Design

Citation: Liu, M.-Y.; Mallya, A.; Tuzel, C.O.; Chen, X., “Unsupervised Network Pretraining via Encoding Human Design”, *IEEE Winter Conference on Applications of Computer Vision (WACV)*, DOI: 10.1109/WACV.2016.7477698, pp. 1-9, March 2016
Contact: Ming-Yu Liu



Over the years, computer vision researchers have spent an immense amount of effort on designing image features for the visual object recognition task. We propose to incorporate this valuable experience to guide the task of training deep neural networks. Our idea is to pretrain the network through the task of replicating the process of hand-designed feature extraction. By learning to replicate the process, the neural network integrates previous research knowledge and learns to model visual objects in a way similar to the hand-designed features. In a succeeding finetuning step, it further learns object-specific representations from labeled data and this boosts its classification power.

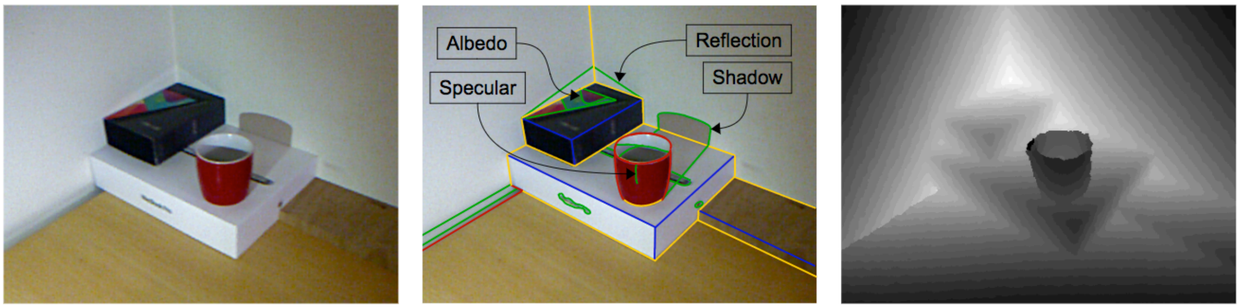
Point-Plane SLAM for Hand-Held 3D Sensors

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, Chen Feng, Srikumar Ramalingam

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.

Semantic Classification of Boundaries from an RGBD Image

Citation: Soni, N.; Namboodiri, A.; Ramalingam, S.; Jawahar, C.V., "Semantic Classification of Boundaries from an RGBD Image", *British Machine Vision Conference (BMVC)*, DOI: 10.5244/C.29.114, ISBN: 1-901725.53-7, pp. 114.1-114.12, September 2015
Contact: Srikumar Ramalingam

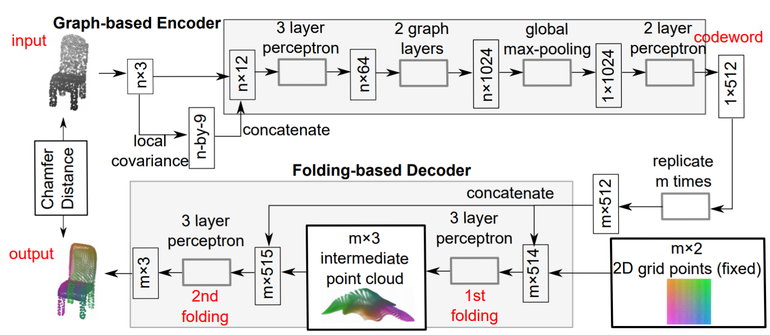


(a) RGB Image (b) Edge Types (c) Depth Map

The problem of labeling the edges present in a single-color image as convex, concave, and occluding entities is one of the fundamental problems in computer vision. Recently, it has been shown that this classification is not straightforward even using RGBD data. In this paper, we propose a novel algorithm using random forest for classifying edges into convex, concave and occluding entities. We release a data set with more than 500 RGBD images with pixel-wise ground labels. Our method produces promising results and achieves an F-score of 0.84.

FoldingNet: Interpretable Unsupervised Learning on 3D Point Clouds

Citation: Yang, Y., Feng, C., Shen, Y., Tian, D., "FoldingNet: Interpretable Unsupervised Learning on 3D Point Clouds," *arXiv*, December 2017
Contacts: Chen Feng, Dong Tian

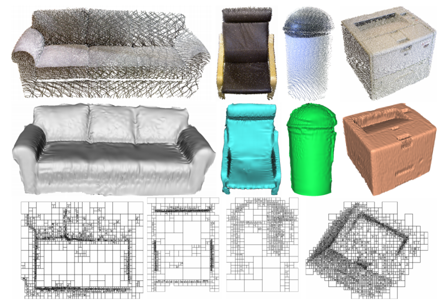


Recent deep networks that directly handle points in a point set, e.g., PointNet, have been state-of-the-art for supervised semantic learning tasks on point clouds such as classification and segmentation. In this work, a novel end-to-end deep auto-encoder is proposed to address unsupervised learning challenges on point clouds. On the encoder side, a graph-based enhancement is enforced to promote local structures on top of PointNet. Then, a novel folding-based approach is proposed in the decoder, which folds a 2D grid onto the underlying 3D object surface of a point cloud. The proposed decoder only uses about 7% as many parameters as a decoder with fully-connected neural networks, yet leads to a more discriminative representation that achieves higher linear SVM classification accuracy than the benchmark.

FasTFit: A Fast T-spline Fitting Algorithm

Citation: Feng, C.; Taguchi, Y., “FasTFit: A Fast T-spline Fitting Algorithm”, *Computer-Aided Design*, DOI: 10.1016/j.cad.2017.07.002, Vol. 92, pp. 11-21, November 2017

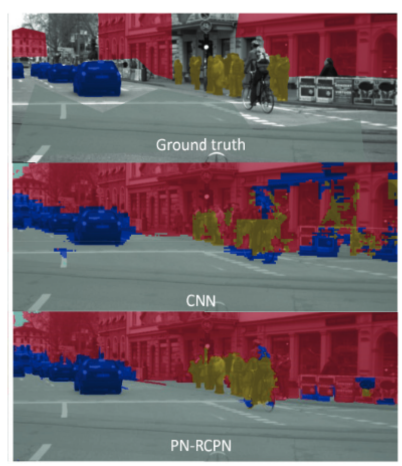
Contacts: Chen Feng, Yuichi Taguchi



T-spline has been recently developed to represent objects of arbitrary shapes using a smaller number of control points than the conventional NURBS or B-spline representations. However, existing methods for fitting a T-spline over a point cloud are slow. By shifting away from the conventional iterative fit-and-refine paradigm, we present a novel split-connect-fit algorithm to more efficiently perform the T-spline fitting. Through adaptively dividing a point cloud into a set of B-spline patches, we first discover a proper topology of T-spline control points, i.e., the T-mesh. We then connect these B-spline patches into a single T-spline surface with different continuity options between neighboring patches according to the data. The T-spline control points are initialized from their correspondences in the B-spline patches, which are refined by using a conjugate gradient method. We demonstrate that our algorithm is at least an order of magnitude faster than state-of-the-art algorithms while providing comparable or better results in terms of quality and conciseness.

Deep Hierarchical Parsing for Semantic Segmentation

Citation: Sharma, A.; Tuzel, C.O.; Jacobs, D., “Deep Hierarchical Parsing for Semantic Segmentation”, *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 1503.02725v2, June 2015

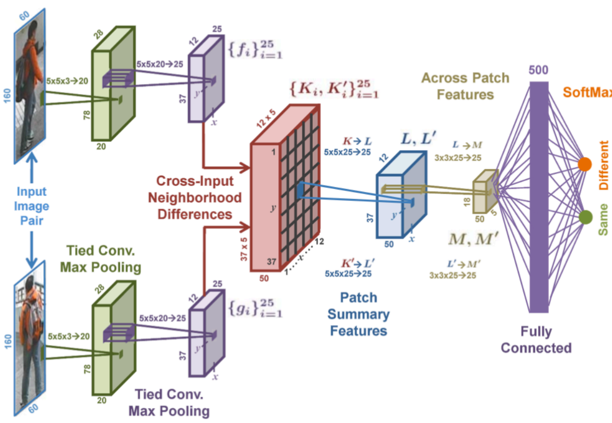


This paper proposes a learning-based approach to scene parsing inspired by deep Recursive Context Propagation Networks (RCPNs). An RCPN is a deep feed-forward neural network that utilizes the contextual information from the entire image, through bottom-up followed by top-down context propagation via random binary parse trees. This improves the feature representation of every super-pixel in the image for better classification into semantic categories. We analyze RCPN and propose two novel contributions to further improve the model. We first analyze the learning of RCPN parameters and discover the presence of bypass error paths in the computation graph of RCPN that can hinder contextual propagation. We tackle this problem by including the classification loss of the internal nodes of the random parse trees in the original RCPN loss function. Secondly, we use an MRF on the parse tree nodes to model the hierarchical dependency present in the output. Both modifications provide performance boosts over the original RCPN and the new system achieves state-of-the-art performance on Stanford Background, SIFT-Flow and Daimler urban datasets.

An Improved Deep Learning Architecture for Person Re-Identification

Citation: Ahmed, E.; Jones, M.J.; Marks, T.K., "An Improved Deep Learning Architecture for Person Re-Identification", *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, DOI: 10.1109/CVPR.2015.7299016, pp. 3908-3916, June 2015

Contacts: Michael J. Jones, Tim K. Marks

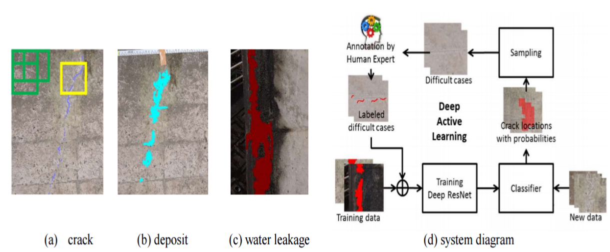


We propose a method for simultaneously learning features and a corresponding similarity metric for person re-identification. Given a pair of images as input, our network outputs a similarity value indicating whether the two input images depict the same person. Novel elements of our architecture include a layer that computes cross-input neighborhood differences, which capture local relationships between the two input images based on midlevel features from each input image. A high-level summary of the outputs of this layer is computed by a layer of patch summary features, which are then spatially integrated in subsequent layers. Our method significantly outperforms the state of the art on both a large data set (CUHK03) and a medium- sized data set (CUHK01).

Deep Active Learning for Civil Infrastructure Defect Detection and Classification

Citation: Feng, C.; Liu, M.-Y.; Kao, C.-C.; Lee, T.-Y., "Deep Active Learning for Civil Infrastructure Defect Detection and Classification", *International Workshop on Computing in Civil Engineering (IWCCE)*, March 3, 2017.

Contacts: Chen Feng, Teng-Yok Lee

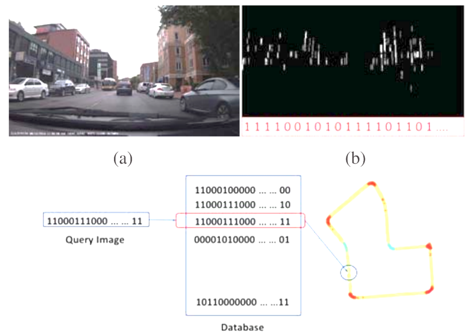


Automatic detection and classification of defects in infrastructure surface images can boost maintenance efficiency. Given enough labeled images, various supervised learning methods have been investigated for this task, including decision trees and support vector machines in previous studies, and deep neural networks more recently. However, in real world applications, labels are harder to obtain than images, due to the limited labeling resources (i.e., experts). We propose a deep active learning system to maximize the performance. A deep residual network is firstly designed for defect detection and classification in an image. Following our active learning strategy, this network is trained as soon as an initial batch of labeled images becomes available. It is then used to select a most informative subset of new images and query labels from experts to retrain the network. Experiments demonstrate performance improvements of our method in comparison to baseline systems, achieving 87.5% detection accuracy.

Barcode: Global Binary Patterns for Fast Visual Inference

Citation: Lee, T.-Y.; Patil, S.; Ramalingam, S.; Taguchi, Y.; Benes, B., "Barcode: Global Binary Patterns for Fast Visual Inference", *International Conference on 3D Vision*, October 2017.

Contacts: Teng-Yok Lee, Yuichi Taguchi

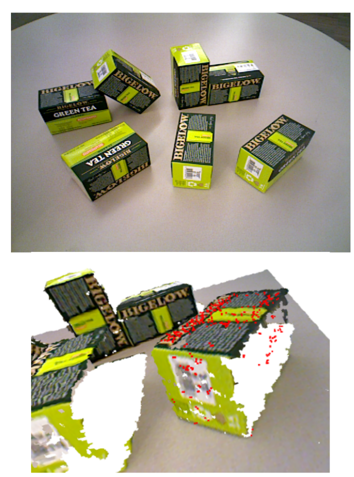


We present Barcode, a global binary descriptor for images captured from a vehicle-mounted camera with two applications: localization and turn classification. Barcode characterizes an image by encoding the distribution of vertical lines into a binary descriptor: in each vertical stripe of an image, if any vertical line exists the corresponding bit is set to 1, otherwise 0. For localization, our approach uses a database of geolocated images, each having its Barcode precomputed during a preprocessing stage. At run time, we first generate the binary descriptor for each image and then use the descriptor to find the location in the database via a Hamming distance metric. For turn classification, we train a deep neural network that uses a set of Barcodes from consecutive images to classify turns (left, right, straight, and stationary). We show that Barcode extraction can be done at 100-1000 Hz, localization at 10 kHz, and turn classification at 1 kHz.

3D Object Discovery and Modeling Using Single RGB-D Images Containing Multiple Object Instances

Citation: Abbeloos, W.; Caccamo, S.; Ataer-Cansizoglu, E.; Taguchi, Y.; Domae, Y., "3D Object Discovery and Modeling Using Single RGB-D Images Containing Multiple Object Instances", *International Conference on 3D Vision*, October 2017

Contacts: Esra Ataer-Cansizoglu, Yuichi Taguchi

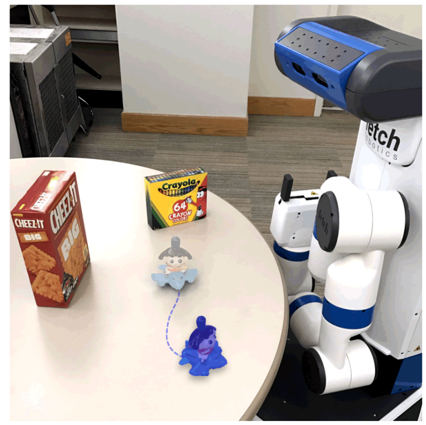


We present a method for unsupervised 3D object discovery, reconstruction, and localization that exploits multiple instances of an identical object contained in a single RGB-D image. The proposed method does not rely on segmentation, scene knowledge, or user input, and thus is easily scalable. Our method aims to find recurrent patterns in a single RGB-D image by utilizing appearance and geometry of salient regions. We extract key-points and match them in pairs based on their descriptors. We then generate triplets of the key-points matching with each other using several geometric criteria to minimize false matches. The relative poses of the matched triplets are computed and clustered to discover sets of triplet pairs with similar relative poses. Triplets belonging to the same set are likely to belong to the same object and are used to construct an initial object model. Detection of remaining instances with the initial object model using RANSAC allows us to further expand and refine the model.

Joint 3D Reconstruction of a Static Scene and Moving Objects

Citation: Caccamo, S.; Ataer-Cansizoglu, E.; Taguchi, Y., "Joint 3D Reconstruction of a Static Scene and Moving Objects", *International Conference on 3D Vision*, October 2017

Contacts: Esra Ataer-Caniszoglu, Yuichi Taguchi

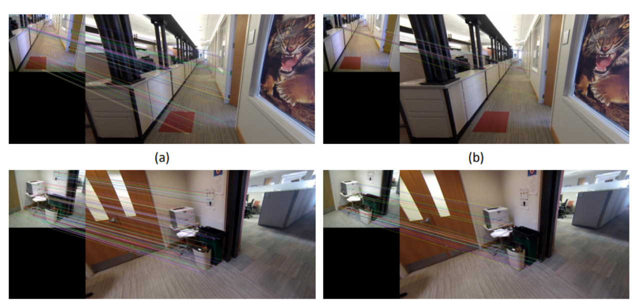


We present a technique for simultaneous 3D reconstruction of static regions and rigidly moving objects in a scene. An RGB-D frame is represented as a collection of features, which are points and planes. We classify the features into static and dynamic regions and grow separate maps, static and object maps, for each of them. To robustly classify the features in each frame, we fuse multiple RANSAC-based registration results obtained by registering different groups of the features to different maps, including (1) all the features to the static map, (2) all the features to each object map, and (3) subsets of the features, each forming a segment, to each object map. This multi-group registration approach is designed to overcome the following challenges: scenes can be dominated by static regions, making object tracking more difficult; and moving object might have larger pose variation between frames compared to the static regions. We show qualitative results from indoor scenes with objects in various shapes. The technique enables on-the-fly object model generation to be used for robotic manipulation.

MonoRGBD-SLAM: Simultaneous Localization and Mapping Using Both Monocular and RGBD Cameras

Citation: Yousif, K.; Taguchi, Y.; Ramalingam, S., "MonoRGBD-SLAM: Simultaneous Localization and Mapping Using Both Monocular and RGBD Cameras", *IEEE International Conference on Robotics and Automation (ICRA)*, DOI: 10.1109/ICRA.2017.7989521, May 2017.

Contacts: Yuichi Taguchi



RGBD SLAM systems have shown impressive results, but the limited field of view (FOV) and depth range of typical RGBD cameras still cause problems for registering distant frames. Monocular SLAM systems, in contrast, can exploit wide-angle cameras and do not have the depth range limitation, but are unstable for texture-less scenes. We present a SLAM system that uses both an RGBD camera and a wide-angle monocular camera for combining the advantages of the two sensors. Experimental results show that our system registers a larger number of frames than using only an RGBD camera, leading to larger-scale 3D reconstruction.

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 Industrial Big Data, necessitates the development of scalable learning algorithms with computational complexity close to linear in the number of data records.

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 car navigation, as well as energy optimization in buildings, can be solved by planning and optimization algorithms. Similarly, a number of problems in robotics, factory automation, and production planning and scheduling can be addressed successfully by means of decision-theoretic planning, sequential optimization, and reinforcement learning methods.

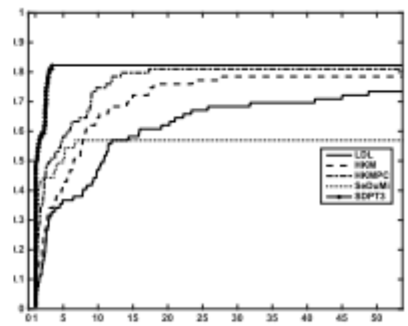
Recent Research

LDL^T Direction in interior point method for semidefinite programming

Citation: Raghunathan, A.U.; Biegler, L.T., LDL^T Direction in interior point method for semidefinite programming”, *SIAM Journal on Optimization*, DOI: 10.1137/16M1105888, vol. 28, iss. 1, pp. 693-734, March 2018.

Contacts: Arvind Raghunathan

We present an interior point method for semidefinite programming where the semidefinite constraints on a matrix X are formulated as nonnegative constraints. The approach was first proposed by Fletcher who also provided analytic expressions for the derivatives of the factors in terms of X and the approach was subsequently utilized in an interior point algorithm by Benson and Vanderbei. However, the evaluation of first and second derivatives has been a bottleneck in such an algorithm. In this paper, we: (i) derive formulae for the first and second derivatives that are efficient and numerically stable to compute, (ii) show that the LDLT based search direction can be viewed in the standard framework of interior point methods for semidefinite programs with comparable computational cost per iteration, (iii) characterize the central path, and (iv) analyze the numerical conditioning of the linear system arising in the algorithm. We provide detailed numerical results on 79 SDP instances from the SDPLIB test set.

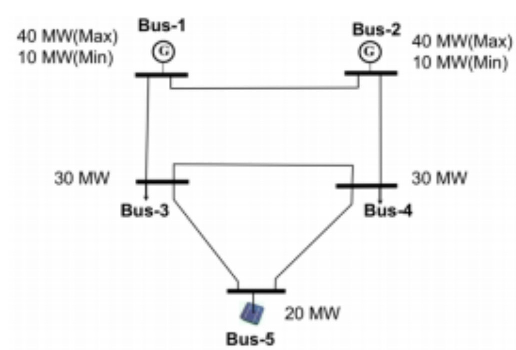


Three-Level Co-optimization Model for Generation Scheduling of Integrated Energy and Regulation Market

Citation: Sun, H.; Takaguchi, Y.; Nikovski, D.N.; Hashimoto, H., “Three-Level Co-optimization Model for Generation Scheduling of Integrated Energy and Regulation Market”, *IEEE Innovative Smart Grid Technologies Conference*, December 2017.

Contacts: Hongbo Sun, Daniel N. Nikovski

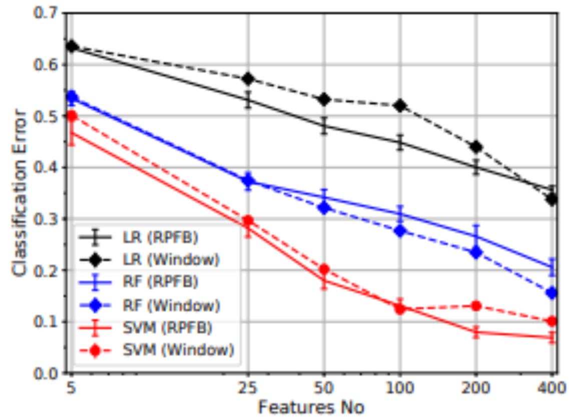
This paper proposes a three-level co-optimization model for determining energy production and regulation reserve schedule in a day-ahead market by minimizing the total cost of unit commitment, generation dispatch, frequency regulation and performance. The unscented transformation and historical profiles are used to generate scenarios for modelling the fluctuations of intermittent renewable and stochastic loads at different time scales. Through detailed modelling and simulation of generation dispatch and frequency regulation, the determined generation schedule can have sufficient reserve capacity and adequate response speed to deal with the renewable and load variations occurred between shorter dispatching and regulating intervals, as well as longer scheduling intervals. Numerical results on a 5-bus sample system are given to demonstrate the effectiveness of proposed method.



Random Projection Filter Bank for Time Series Data

Citation: Pourazarm, S.; Farahmand, A.-M.; Nikovski, D.N., "Random Projection Filter Bank for Time Series Data", *Advances in Neural Information Processing Systems (NIPS)*, December 2017

Contacts: Daniel N. Nikovski

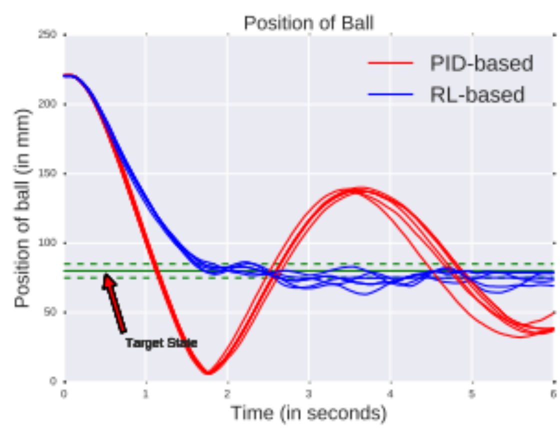


We propose Random Projection Filter Banks (RPFBs) as a generic and simple approach to extract features from time series data. An RPFB is a set of randomly generated stable autoregressive filters that are convolved with the input time series to generate the features. These features can be used by any conventional machine learning algorithm for solving tasks such as time series prediction, classification with time series data, etc. Different filters in RPFB extract different aspects of the time series, and together they provide a reasonably good summary of the time series. RPFB is easy to implement, fast to compute, and parallelizable. We provide an error upper bound indicating that RPFB provides a reasonable approximation to a class of dynamical systems. The empirical results in a series of synthetic and real-world problems show that RPFB is an effective method to extract features from time series.

Learning to Regulate Rolling Ball Motion

Citation: Jha, D.; Yerazunis, W.S.; Nikovski, D.N.; Farahmand, A.-M., "Learning to Regulate Rolling Ball Motion", *IEEE Symposium on Computational Intelligence in Engineering Solutions*, DOI: 10.1109/SSCI.2017.8285376, November 2017.

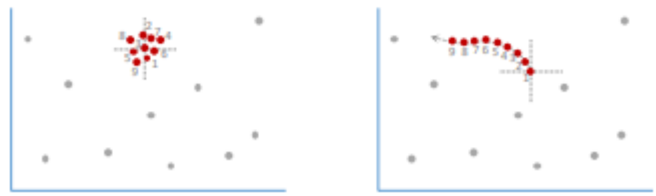
Contacts: Devesh Jha, William S. Yerazsunis, Daniel N. Nikovski



In this paper, we present a problem of regulating the motion of a rolling ball in a one-dimensional space in the presence of non-linear effects of friction and contact. The regulation problem is solved using a model-based reinforcement learning technique. A Gaussian process model is learned to make predictions on the motion of the ball and then, the predictive model is used to solve for the control policy using dynamic programming by estimating the value functions. Several results are shown to demonstrate the simple, yet interesting motion dynamics for the ball. Our hope is that the proposed system will serve as a simple benchmark system for reinforcement and robot learning.

Matrix Profile VII: Time Series Chains: A New Primitive for Time Series Data Mining

Citation: Zhu, Y.; Imamura, M.; Nikovski, D.N.; Keogh, E., “Matrix Profile VII: Time Series Chains: A New Primitive for Time Series Data Mining”, *International Conference on Data Mining*, DOI: 10.1109/ICDM.2017.79, November 2017.
Contacts: Daniel N. Nikovski

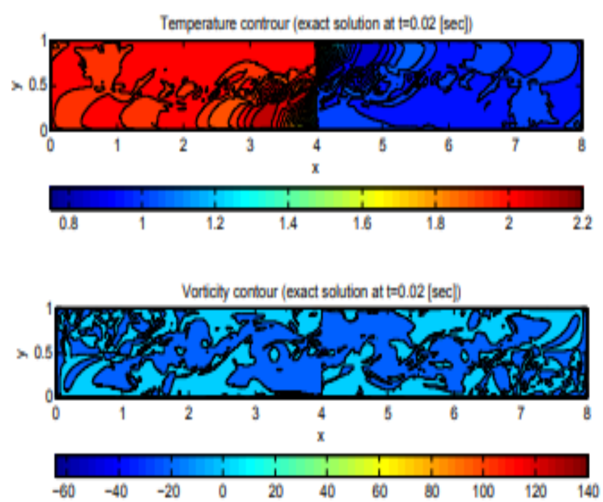


Since their introduction over a decade ago, time series motifs have become a fundamental tool for time series analytics, finding diverse uses in dozens of domains. We introduce Time Series Chains, which are related to, but distinct from, time series motifs. Informally, time series chains are a temporally ordered set of subsequence patterns, such that each pattern is similar to the pattern that preceded it, but the first and last patterns are arbitrarily dissimilar. In the discrete space, this is similar to extracting the text chain "hit, hot, dot, dog" from a paragraph. The first and last words have nothing in common, yet they are connected by a chain of words with a small mutual difference. Time series chains can capture the evolution of systems and help predict the future. As such, they potentially have implications for prognostics. In this work, we introduce a robust definition of time series chains, and a scalable algorithm that allows us to discover them in massive datasets.

Learning-based Robust Stabilization for Reduced-Order Models of 2D and 3D Boussinesq Equations

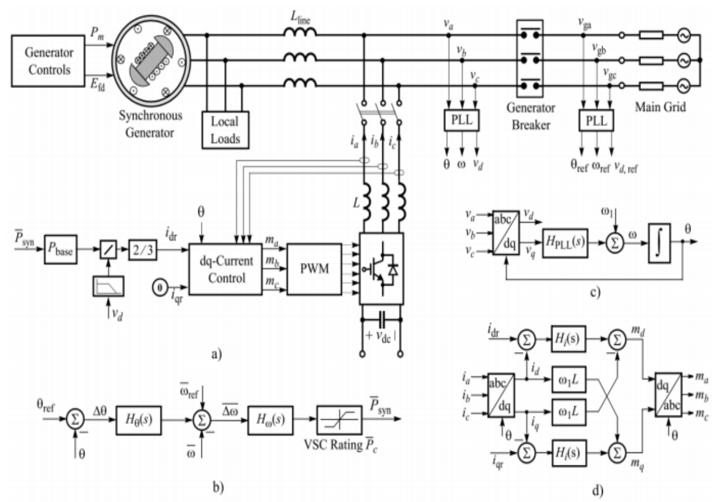
Citation: Benosman, M.; Borggaard, J.; Kramer, B., “Learning-based Robust Stabilization for Reduced-Order Models of 2D and 3D Boussinesq Equations”, *Journal of Applied Mathematical Modeling*, DOI: 10.1016/j.apm.2017.04.032, vol. 49, pp. 162-181, September 2017.
Contacts: Mouhacine Benosman

We present some results on the stabilization of reduced-order models (ROMs) for thermal fluids. The stabilization is achieved using robust Lyapunov control theory to design a new closure model that is robust to parametric uncertainties. Furthermore, the free parameters in the proposed ROM stabilization method are optimized using a data-driven multi-parametric extremum seeking (MES) algorithm. The 2D and 3D Boussinesq equations provide challenging numerical test cases that are used to demonstrate the advantages of the proposed method.



VSC Based Active Synchronizer for Generators

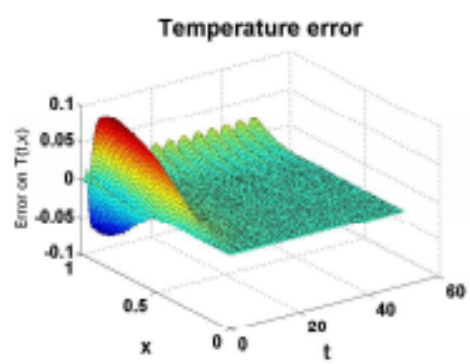
Citation: Shah, S.; Sun, H.; Nikovski, D.N.; Zhang, J., "VSC Based Active Synchronizer for Generators", *IEEE Transactions on Energy Conversion*, DOI: 10.1109/TEC.2017.2728718, vol. 33, iss. 1, pp. 116-125, July 2017.
Contacts: Daniel N. Nikovski, Jinyun Zhang



Fast synchronization of generators and microgrids will be a critical technology in future power systems with high penetration of non-dispatchable power resources. Existing synchronization methods rely on generator controls and their performance is limited by the generator characteristics. Speed of microgrid synchronization is further limited by the communication link among generation units. These factors lead to a slow and sometimes faulty synchronization, predominantly because of the phase mismatch during interconnection. This paper frames the generator synchronization problem as a phaselocked loop (PLL) design problem and introduces a voltage source converter (VSC) based synchronizer for implementing the PLL based active synchronization method.

Gaussian Processes-based Parametric Identification for Dynamical Systems

Citation: Benosman, M.; Farahmand, A.-M., "Gaussian Processes-based Parametric Identification for Dynamical Systems", *World Congress of the International Federation of Automatic Control (IFAC)*, July 2017.
Contacts: Mouhacine Benosman

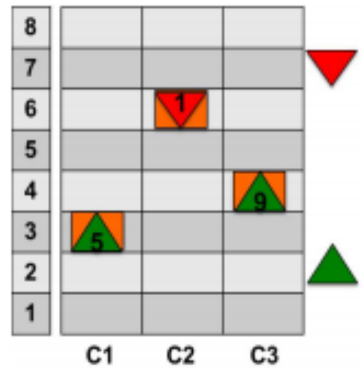


Wwe present some results on parametric identification for dynamical systems. More specifically, we consider the general case of dynamics described by partial differential equations (PDEs), which includes the special case of ordinary differential equations (ODEs). We follow a stochastic approach and formulate the identification problem as a Gaussian process optimization with respect to the unknown parameters of the PDE. We use proper orthogonal decomposition (POD) model reduction theory together with a data-driven Gaussian Process Upper Confidence Bound (GP-UCB), to solve the identification problem. The proposed approach is validated on the coupled Burgers' equation benchmark.

Submodular Function Maximization for Group Elevator Scheduling

Citation: Ramalingam, S.; Raghunathan, A.U.; Nikovski, D.N., "Submodular Function Maximization for Group Elevator Scheduling", *International Conference on Automated Planning and Scheduling (ICAPS)*, June.

Contacts: Arvind Raghunathan, Daniel N. Nikovski

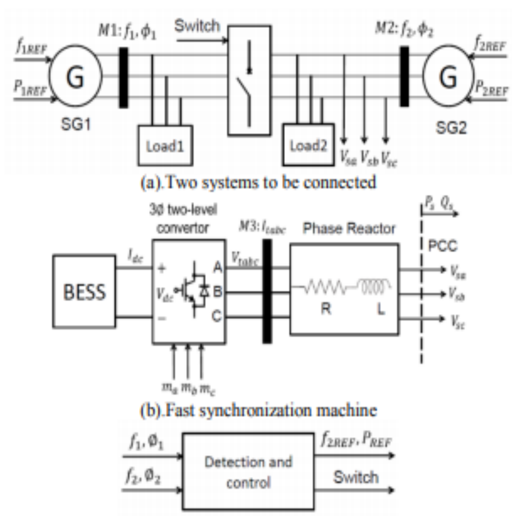


We propose a novel approach for group elevator scheduling by formulating it as the maximization of a submodular function under a matroid constraint. In particular, we model the total waiting time of passengers using a quadratic Boolean function. The unary and pairwise terms in the function denote the waiting time for single and pairwise allocation of passengers to elevators, respectively. We show that this objective function is submodular. The matroid constraints ensure that every passenger is allocated to exactly one elevator. We use a greedy algorithm to maximize the submodular objective function, and derive provable guarantees on the optimality of the solution. We tested our algorithm using Elevate 8, a commercial-grade elevator simulator that allows simulation with a wide range of elevator settings. We achieve significant improvements over the existing algorithms.

A Novel BESS-based Fast Synchronization Method for Power Grids

Citation: Wang, G.; Sun, H.; Nikovski, D.N.; Zhang, J., "A Novel BESS-based Fast Synchronization Method for Power Grids", *IEEE PES PowerTech*, DOI: 10.1109/PTC.2017.7981044, June 2017.

Contacts: Hongbo Sun, Daniel N. Nikovski, Jinyun Zhang

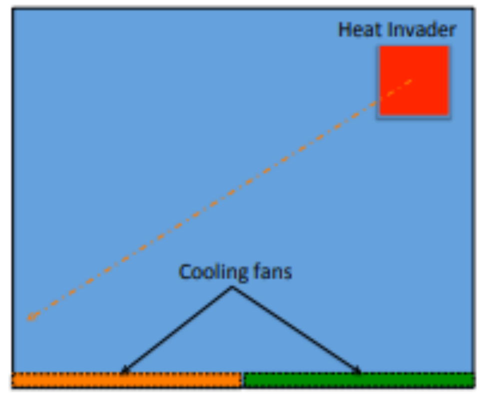


This paper introduces a novel method for synchronizing two energized AC grids through a fast synchronization machines, which integrates a battery energy storage system (BESS) with a grid-imposed frequency voltage source power converter. The grid-imposed power converter is used to automatically provide the desired amount of power to the synchronous generators, and the BESS is connected to the DC side of the power converter, which exchanges energy with the grids. This method can achieve fast synchronization of grid frequencies and phases through active and automatic power exchanges between the battery based power converter and the grids. Compared with traditional methods, the synchronization time can be reduced by an order of magnitude using the proposed method.

Deep Reinforcement Learning for Partial Differential Equation Control

Citation: Farahmand, A.-M.; Nabi, S.; Nikovski, D.N., "Deep Reinforcement Learning for Partial Differential Equation Control", *American Control Conference (ACC)*, DOI: 10.23919/ACC.2017.7963427, May 2017.

Contacts: Saleh Nabi, Daniel N. Nikovski

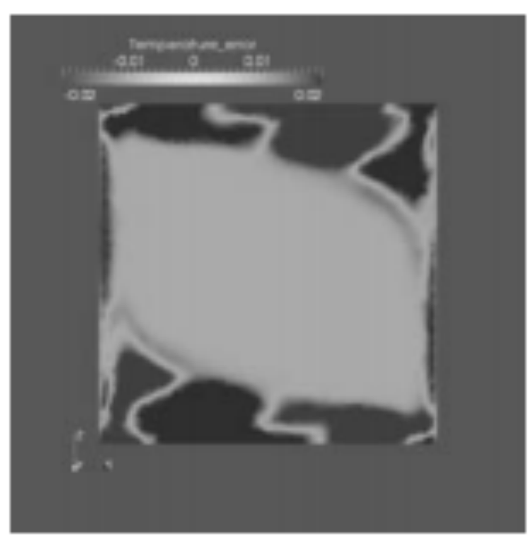


This paper develops a data-driven method for control of partial differential equations (PDE) based on deep reinforcement learning (RL) techniques. We design a Deep Fitted Q-Iteration (DFQI) algorithm that works directly with a high-dimensional representation of the state of PDE, thus allowing us to avoid the model order reduction step common in the conventional PDE control design approaches. We apply the DFQI algorithm to the problem of flow control for timevarying 2D convection-diffusion PDE, as a simplified model for heating, ventilating, air conditioning (HVAC) control design in a room. We also study the transfer learning of a policy learned for a PDE to another one.

Robust POD Model Stabilization for the 3D Boussinesq Equations Based on Lyapunov Theory and Extremum Seeking

Citation: Benosman, M.; Borggaard, J.; Kramer, B., "Robust POD Model Stabilization for the 3D Boussinesq Equations Based on Lyapunov Theory and Extremum Seeking", *American Control Conference (ACC)*, DOI: 10.23919/ACC.2017.7963218, May 2017.

Contacts: Mouhacine Benosman



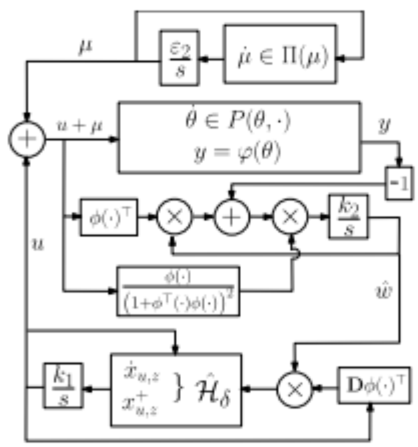
We present new results on robust model reduction for partial differential equations. Our contribution is threefold: 1.) The stabilization is achieved via closure models for reduced order models (ROMs), where we use Lyapunov robust control theory to design a new stabilizing closure model that is robust with respect to parametric uncertainties; 2.) The free parameters in the proposed ROM stabilization method are autotuned using a data-driven multi-parametric extremum seeking (MES) optimization algorithm; and 3.) The challenging 3D Boussinesq equation numerical test-bed is used to demonstrate the advantages of the proposed method.

A Neuro-Adaptive Architecture for Extremum Seeking Control Using Hybrid Learning Dynamics

Citation: Benosman, M., “A Neuro-Adaptive Architecture for Extremum Seeking Control Using Hybrid Learning Dynamics”, *American Control Conference (ACC)*, DOI: 10.23919/ACC.2017.7963009, April 2017.

Contacts: Mouhacine Benosman

This paper presents a novel approach to achieve online multivariable hybrid optimization of response maps associated to set-valued dynamical systems, without requiring the use of averaging theory. In particular, we propose a prescriptive framework for the analysis and design of a class of adaptive control architectures based on neural networks (NN) and learning dynamics described by hybrid dynamical systems (HDS). The NNs are used as model-free gradient approximators that are online tuned in order to obtain an arbitrarily precise estimation on a compact set of the gradient of the response map of the system under control. For the closed-loop system a semi-global practical asymptotic stability result is obtained, and the results are illustrated via numerical examples.

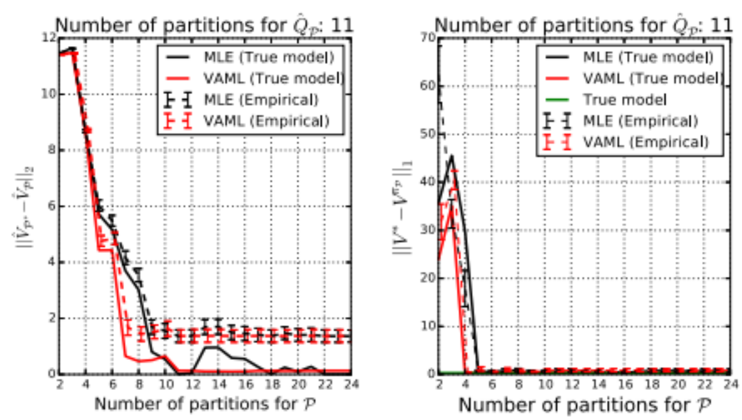


Treemaps and the Visual Comparison of Hierarchical Multidimensional Data

Citation: Farahmand, A.-M.; Barreto, A.M.S.; Nikovski, D.N., “Value-Aware Loss Function for Model Learning in Reinforcement Learning”, Artificial Intelligence and Statistics (AISTATS), vol. 54, April 2017.

Contacts: Daniel N. Nikovski

We consider the problem of estimating the transition probability kernel to be used by a model-based reinforcement learning (RL) algorithm. We argue that estimating a generative model that minimizes a probabilistic loss, such as the log-loss, is an overkill because it does not take into account the underlying structure of decision problem and the RL algorithm that intends to solve it. We introduce a loss function that takes the structure of the value function into account. We provide a finite-sample upper bound for the loss function showing the dependence of the error on model approximation error, number of samples, and the complexity of the model space. We also empirically compare the method with the maximum likelihood estimator on a simple problem



Speech & Audio

The speech and audio group pursues a range of challenging machine-perception problems, involving acoustic signals, human language, and everything in between. Our primary areas of research cover speech enhancement and separation, speech recognition, natural language processing, and acoustic analysis.

In the area of speech enhancement and separation, we have developed novel techniques to effectively separate the speech of simultaneous speakers, with either single microphone or multiple microphone configurations. Prior work has also addressed the suppression of various types of background noises from the speech signal.

For speech recognition, we have been advancing the state-of-the-art in end-to-end deep learning approaches, which simplify conventional systems into single network architecture that can be fully optimized without the need for expert knowledge such as phoneme set, pronunciation lexicon, and tokenization. Furthermore, we have enabled extensions for multiple languages, multiple simultaneous speakers, and their combination.

Our efforts in natural language processing target advanced spoken dialog systems based on neural conversation models, in which we generate system responses automatically based on the user input directly, without the need for any intermediate symbols or annotation. We extend this work to scene-aware dialog systems that respond to multiple audio-visual cues in the scene.

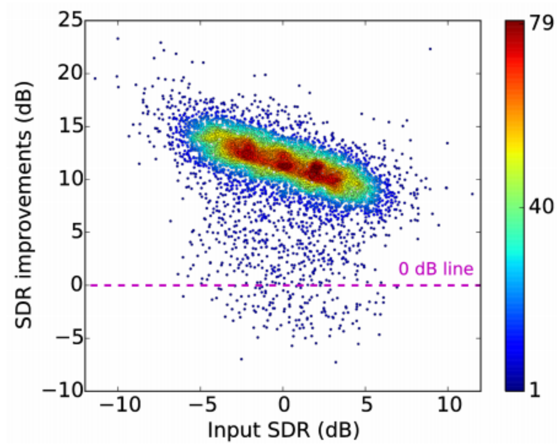
Research in the area of acoustic analysis targets the diagnostics and optimization of industrial machines for improved efficiency and cost reduction. We also aim to classify general sounds in complex mixtures in order to enable more comprehensive scene understanding.

Recent Research

Single-Channel Multi-Speaker Separation using Deep Clustering

Citation: Isik, Y.; Le Roux, J.; Chen, Z.; Watanabe, S.; Hershey, J.R., "Single-Channel Multi-Speaker Separation using Deep Clustering", *Interspeech*, September 8, 2016.

Contact: Jonathan Le Roux

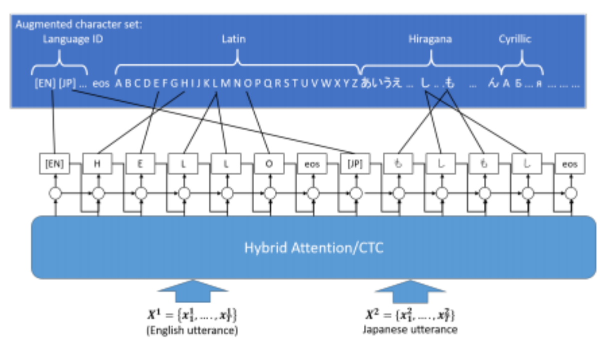


Deep clustering is a recently introduced deep learning architecture that uses discriminatively trained embeddings as the basis for clustering. It was recently applied to spectrogram segmentation, resulting in impressive results on speaker-independent multi-speaker separation. In this paper we extend the baseline system with an end-to-end signal approximation objective that greatly improves performance on a challenging speech separation. The new signal approximation objective, combined with end-to-end training, produces unprecedented performance, reducing the word error rate (WER) from 89.1% down to 30.8%. This represents a major advancement towards solving the cocktail party problem.

Language Independent End-to-End Architecture For Joint Language and Speech Recognition

Citation: Watanabe, S.; Hori, T.; Hershey, J.R., "Language Independent End-to-End Architecture For Joint Language and Speech Recognition", *IEEE Workshop on Automatic Speech Recognition and Understanding (ASRU)*, DOI: 10.1109/ASRU.2017.8268945, December 2017.

Contact: Takaaki Hori

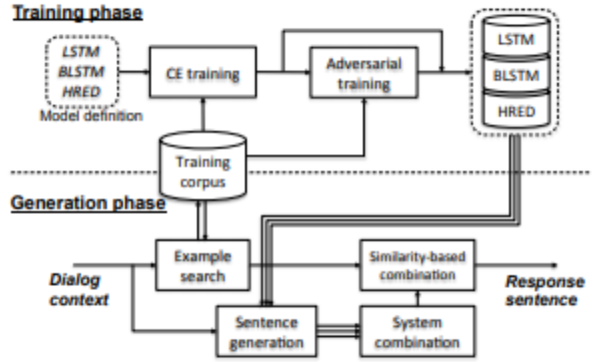


End-to-end automatic speech recognition (ASR) can significantly reduce the burden of developing ASR systems for new languages, by eliminating the need for linguistic information such as pronunciation dictionaries. This also creates an opportunity, which we fully exploit in this paper, to build a monolithic multilingual ASR system with a language-independent neural network architecture. We present a model that can recognize speech in 10 different languages, by directly performing grapheme (character/chunked-character) based speech recognition. The model is based on our hybrid attention/connectionist temporal classification (CTC) architecture which has previously been shown to achieve the state-of-the-art performance in several ASR benchmarks. The model can jointly identify the language and recognize the speech, automatically formatting the recognized text in the appropriate character set.

Sequence Adversarial Training and Minimum Bayes Risk Decoding for End-to-end Neural Conversation Models

Citation: Wang, W.; Koji, Y.; Harsham, B.A.; Hori, T.; Hershey, J.R., "Sequence Adversarial Training and Minimum Bayes Risk Decoding for End-to-end Neural Conversation Models", *Dialog System Technology Challenges*, December 2017.

Contacts: Bret A. Harsham, Takaaki Hori

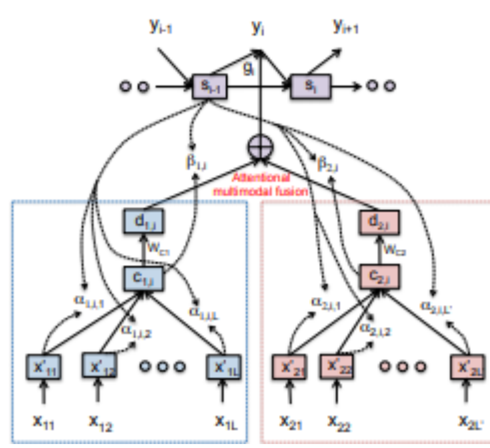


We present a neural conversation system that incorporates multiple sequence-to-sequence models, sequence adversarial training, example-based response selection, and BLEU-based Minimum Bayes Risk (MBR) decoding. The system was trained and tested using the 6th Dialog System Technology Challenges (DSTC6) Twitter help-desk dialog task. Experimental results demonstrate that adversarial training and the example-based method are effective in improving human rating score while system combination with MBR decoding improves objective measures such as BLEU and METEOR scores. Moreover, we investigate extension of the reward function for sequence adversarial training in order to balance subjective and objective scores.

Attention-Based Multimodal Fusion for Video Description

Citation: Hori, C.; Hori, T.; Lee, T.-Y.; Zhang, Z.; Harsham, B.A.; Hershey, J. R.; Marks, T.K.; Sumi, K, "Attention-Based Multimodal Fusion for Video Description", *IEEE International Conference on Computer Vision (ICCV)*, DOI: 10.1109/ICCV.2017.450, October 2017.

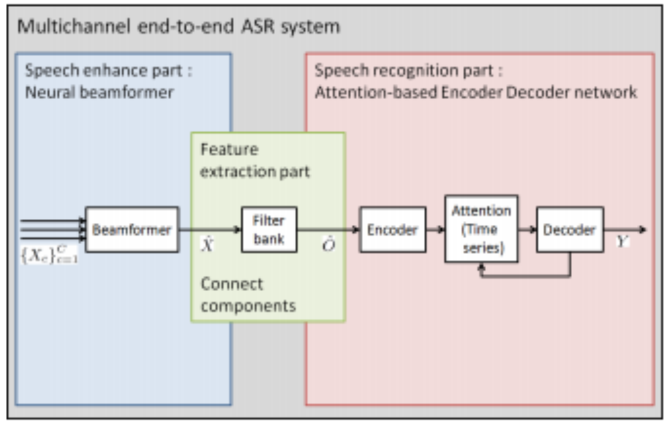
Contacts: Chiori Hori, Takaaki Hori, Teng-Yok Lee, Ziming Zhang, Bret A. Harsham, Tim K. Marks



Far-field speech recognition in noisy and reverberant conditions is commonly addressed by acquiring a speech signal from multiple microphones and performing beamforming over them. In this paper, we propose to use a recurrent neural network with long short-term memory (LSTM) architecture to adaptively estimate real-time beamforming filter coefficients to cope with non- stationary environmental noise and the dynamic nature of source and microphone positions that results in a set of time-varying room impulse responses. The proposed system achieves 7.97% absolute gain over baseline systems with no beamforming on CHiME-3 real evaluation set.

Unified Architecture for Multichannel End-to-End Speech Recognition with Neural Beamforming

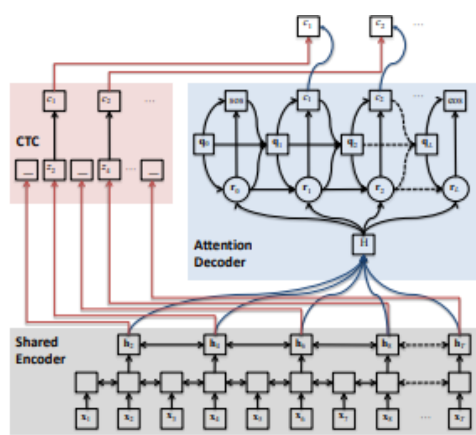
Citation: Ochiai, T.; Watanabe, S.; Hori, T.; Hershey, J.R.; Xiao, X., "Unified Architecture for Multichannel End-to-End Speech Recognition with Neural Beamforming", *IEEE Journal of Selected Topics in Signal Processing*, DOI: 10.1109/JSTSP.2017.2764276, Vol. 11, No. 8, pp. 1274-1288, October 2017.
Contact: Takaaki Hori



Although most existing end-to-end frameworks have mainly focused on ASR in clean environments, our aim is to build more realistic end-to-end systems in noisy environments. To handle such challenging noisy ASR tasks, we study multichannel end-to-end ASR architecture, which directly converts multichannel speech signal to text through speech enhancement. This architecture allows speech enhancement and ASR components to be jointly optimized to improve the end-to-end ASR objective and leads to an end-to-end framework that works well in the presence of strong background noise.

Hybrid CTC/Attention Architecture for End-to-End Speech Recognition

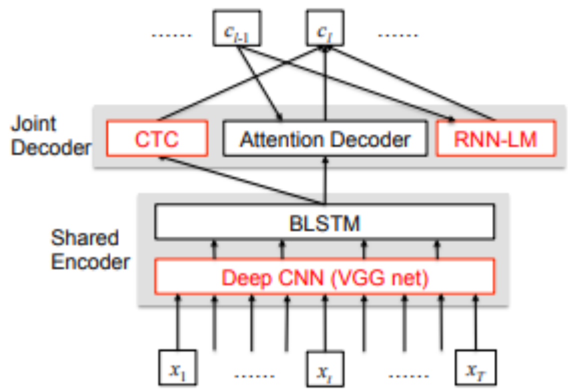
Citation: Watanabe, S.; Hori, T.; Kim, S.; Hershey, J.R.; Hayashi, T., "Hybrid CTC/Attention Architecture for End-to-End Speech Recognition", *IEEE Journal of Selected Topics in Signal Processing*, DOI: 10.1109/JSTSP.2017.2763455, ISSN: 1941-0484, Vol. 11, No. 8, pp. 1240-1253, October 2017.
Contacts: Takaaki Hori



There are two major types of end-to-end architectures for ASR: connectionist temporal classification (CTC) uses Markov assumptions to efficiently solve sequential problems by dynamic programming and attention-based methods use an attention mechanism to perform alignment between acoustic frames and recognized symbols. This paper proposes hybrid CTC/attention end-to-end ASR, which effectively utilizes the advantages of both architectures in training and decoding. During decoding, we perform joint decoding by combining both attention-based and CTC scores in a one-pass beam search algorithm to further eliminate irregular alignments. Experiments with English (WSJ and CHiME-4) tasks demonstrate the effectiveness of the proposed multi-objective learning over both the CTC and attention-based encoder–decoder baselines.

Advances in Joint CTC-Attention based End-to-End Speech Recognition with a Deep CNN Encoder and RNN-LM

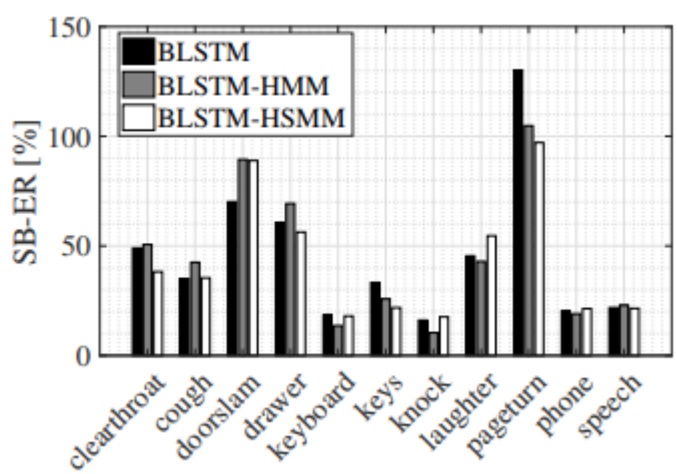
Citation: Hori, T.; Watanabe, S.; Zhang, Y.; Chan, W., "Advances in Joint CTC-Attention based End-to-End Speech Recognition with a Deep CNN Encoder and RNN-LM", *Interspeech*, August 2017.
Contact: Takaaki Hori



We present a state-of-the-art end-to-end Automatic Speech Recognition (ASR) model. We learn to listen and write characters with a joint Connectionist Temporal Classification (CTC) and attention-based encoder-decoder network. The encoder is a deep Convolutional Neural Network (CNN) based on the VGG network. The CTC network sits on top of the encoder and is jointly trained with the attention-based decoder. During the beam search process, we combine the CTC predictions, the attention-based decoder predictions and a separately trained LSTM language model. We achieve a 5-10% error reduction compared to prior systems on spontaneous Japanese and Chinese speech, and our end-to-end model beats out traditional hybrid ASR systems.

Duration-Controlled LSTM for Polyphonic Sound Event Detection

Citation: Hayashi, T.; Watanabe, S.; Toda, T.; Hori, T.; Le Roux, J.; Takeda, K., "Duration-Controlled LSTM for Polyphonic Sound Event Detection", *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, DOI: 10.1109/TASLP.2017.2740002, Vol. 25, No. 11, August 2017.
Contacts: Takaaki Hori, Jonathan Le Roux



This paper presents a new hybrid approach called duration-controlled long short-term memory (LSTM) for polyphonic Sound Event Detection (SED). It builds upon a state-of-the-art SED method which performs frame-by-frame detection using a bidirectional LSTM recurrent neural network (BLSTM), and incorporates a duration-controlled modeling technique based on a hidden semi-Markov model (HSMM). The proposed approach makes it possible to model the duration of each sound event precisely and to perform sequence-by-sequence detection without having to resort to thresholding, as in conventional frame-by-frame methods.

Signal Processing

The Signal Processing Group conducts fundamental and applied research in the areas of wireless and optical communications, computational sensing, and optical and RF semiconductor devices. Our research has application to product areas such as terrestrial and trans-oceanic optical networks, train and automotive connectivity, mobile cellular, networking for IoT, RF power amplifiers, vehicular radars, non-contact sensing and radar imaging.

Wireless research focuses on the development of novel physical and network layer algorithms, RF device design with advanced signal processing, to enable high reliability wireless networks for IoT networks, 5G/millimeter wave systems and vehicular networks. We also seek to apply signal processing and communications knowledge to areas such as cooperative robotics, radio-based localization, and applied optimization algorithms for applications such as IoT.

Optical research focuses on transceiver 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 coherent optical communications applications.

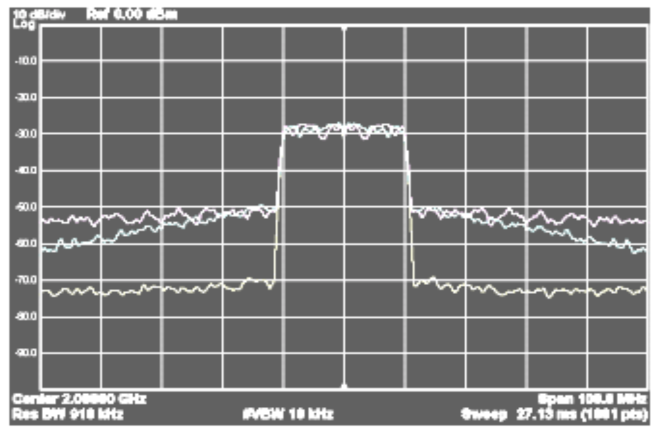
Computational sensing research exploits widely available computational power to overhaul the signal acquisition paradigm and significantly enhance sensing capabilities. Our research aims to fundamentally understand how signals behave and propagate in the environment and develops reconstruction algorithms to recover these signals.

Recent Research

Truly Aliasing-Free Digital RF-PWM Power Coding Scheme for Switched-Mode Power Amplifiers

Citation: Tanovic, O.; Ma, R., "Truly Aliasing-Free Digital RF-PWM Power Coding Scheme for Switched-Mode Power Amplifiers", *IEEE Radio and Wireless Symposium (RWS)*, DOI: 10.1109/RWS.2018.8304948, March 2018

Contacts: Rui Ma

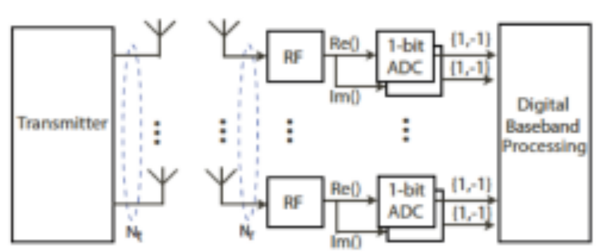


This paper presents a novel method for multilevel power coding and upconversion to RF frequency, by the means of a digital radio-frequency pulse width modulation (RF-PWM). Delta-sigma modulation and memoryless predistortion are used to cancel spectral aliasing effects, inherent to digital RFPWM operation, and achieve high linearity of the transmitter. In this method, time-domain characterization of a multilevel digital RF-PWM was fully exploited in order to provide optimal parameter selection for the Delta-sigma modulation, which in turn enables aliasing-free digital RF-PWM runing at reasonable clock speeds.

On Angular-Domain Chanel Estimation for One-Bit Massive MIMO Systems with Fixed and Time-Varying Thresholds

Citation: Wang, P.; Li, J.; Pajovic, M.; Boufounos, P.T.; Orlik, P.V., "On Angular-Domain Chanel Estimation for One-Bit Massive MIMO Systems with Fixed and Time-Varying Thresholds", *Asilomar Conference on Signals, Systems and Computers (ACSSC)*, DOI: 10.1109/ACSSC.2017.8335511, December 2017.

Contacts: Pu (Perry) Wang, Milutin Pajovic, Petros T. Boufounos, Philip V. Orlik

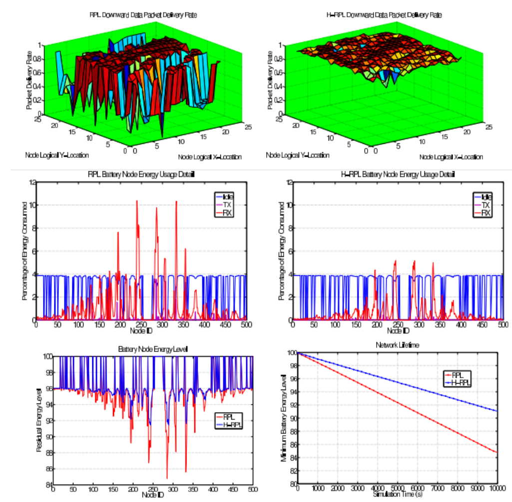


This paper considers angular-domain channel estimation for massive MIMO systems with one-bit analog-to-digital converters (ADCs) equipped at base stations for the sake of lower power consumption and reduced hardware cost. We characterize analytical performance, in terms of the Cramer-Rao bound (CRB), on estimating the two-dimensional channel matrix (including angle-of-departure, angle-of-arrival and associated channel path gains) in the angular-domain representation. Our analysis provides a simple tool to compare the channel estimation performance among several one-bit quantization schemes. Particularly, we study the performance trade-off between fixed (zero-threshold) and time-varying one-bit quantization schemes. Numerical results are provided for analytical performance verification as a function of SNR and the number of pilots.

Resource Aware Hierarchical Routing in Heterogeneous Wireless IoT Networks

Citation: Guo, J.; Orlik, P.V.; Ishibashi, K., "Resource Aware Hierarchical Routing in Heterogeneous Wireless IoT Networks", I*EEE International Conference on Ubiquitous and Future Networks*, p. 599- 604, July 5, 2016.

Contacts: Jianlin Guo, Philip V. Orlik

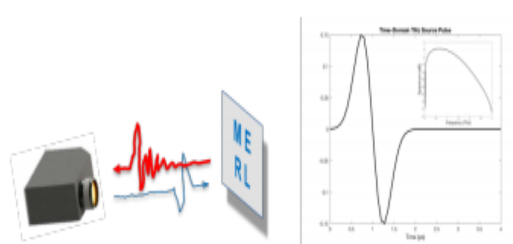


Routing algorithms consume the resources of network nodes. Different routing algorithms require different amounts of the resources. Nodes at different positions of the network topology require different amounts of the resources. Routing algorithms must adapt to both available resources and required resources of the nodes. The IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) defines four modes of operation (MOPs), but allows only one MOP for all routers in a network. This paper presents a resource aware hierarchical RPL (H-RPL) to realize mixed MOPs and resource adaptation in heterogeneous wireless IoT networks. Taking routing preferences of the nodes into account, H-RPL also applies heterogeneous routing metrics and objective functions in hierarchical network topology construction. Simulation results show that H-RPL can improve upward data packet delivery rate by 7%, downward data packet delivery rate by 25% and extend network lifetime by 78%.

Bayesian Coupled-Pixel Terahertz-TDS Imaging

Citation: Wang, P.; Orlik, P.V.; Wang, B.; Ma, R.; Teo, K.H.; Tsujita, W.; Sadamoto, K.; Sawa, Y., "Bayesian Coupled-Pixel Terahertz-TDS Imaging", *42nd Int. Conference on Infrared*, Millimeter and Terahertz Waves (IRMMW-THz 2017), DOI: 10.1109/IRMMW-THz.2017.8067174, August 2017.

Contacts: Pu (Perry) Wang, Philip V. Orlik, Bingnan Wang, Rui Ma, Koon Hoo Teo



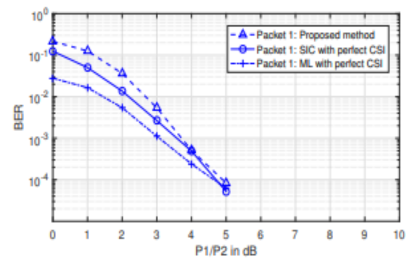
(a) (b)

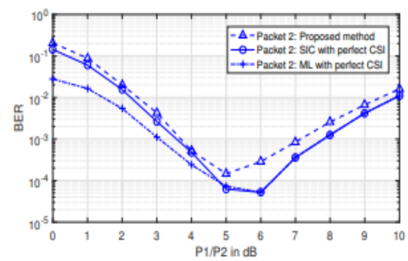
This paper considers Terahertz (THz) sensing of contents on a single-layer object with time-domain spectroscopy (TDS) in a reflection mode. With an extremely small pulse width, the THz-TDS sensing is highly sensitive to non-ideal configurations such as a tilted or uneven sample, depth variation due to mechanical scanning operations, and intra-layer reflections. In this paper, we follow an existing alternative minimization scheme and propose a simple modification to take into account, in addition to the binary nature of reflection coefficients, the two-dimensional block feature of the content (i.e., letters and shapes) in the sample. Preliminary results with synthetic datasets show the effectiveness of our method.

Packet Separation in Random Access Channels Via Approximate Sparse Recovery

Citation: Shulkind, G.; Pajovic, M.; Orlik, P.V., “Packet Separation in Random Access Channels Via Approximate Sparse Recovery”, *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, DOI: 10.1109/GlobalSIP.2017.8309085, November 2017.

Contacts: Milutin Pajovic, Philip V. Orlik





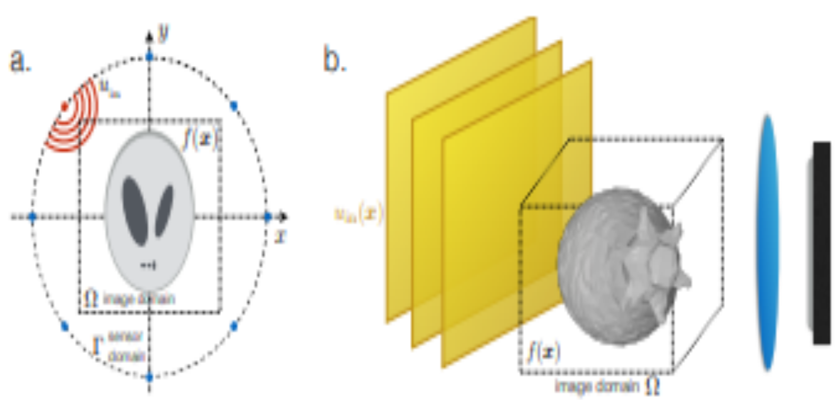
In various wireless applications, a receiver picks up data packets from multiple users where the packets share a common preamble, but otherwise carry different payloads, are not in temporal sync and are frequency shifted due to Doppler effects and oscillator imperfections. We pose the problem of identifying the number of interfering packets and extracting the payloads as one of finding a sparse representation in a redundant dictionary. However, because of large size of the dictionary due to unknown packet payloads, direct application of conventional recovery methods does not lead to computationally tractable estimation schemes. To overcome this issue, we propose Orthogonal Matching Pursuit with Approximate Atoms (OMP-AA) algorithm aimed to facilitate identification of packet collisions and payload extraction. A simulation study shows that the proposed method performs well compared to an oracle estimator which has perfect knowledge of the packet parameters.

SEAGLE: Robust Computational Imaging under Multiple Scattering

Citation: Liu, H.-Y.; Liu, D.; Mansour, H.; Boufounos, P.T.; Waller, L.; Kamilov, U., “SEAGLE: Robust Computational Imaging under Multiple Scattering”, *OSA Imaging and Applied Optics Congress*, DOI: 10.1364/MATH.2017.MM4C.1, June 2017.

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

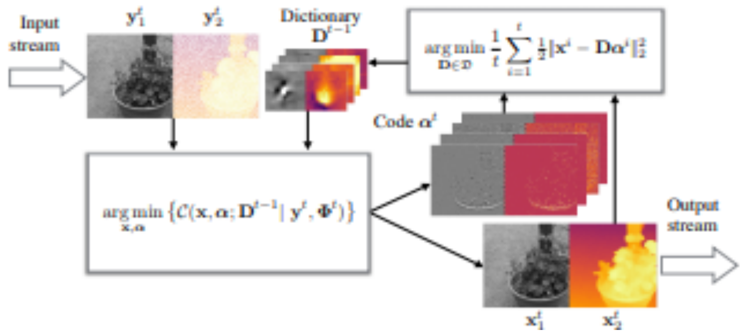
Multiple scattering of light as it passes through an object is a fundamental problem limiting the performance of imaging systems. We describe a new technique for robust imaging under multiple scattering based on a nonlinear scattering model and sparse-regularization.



Online Convolutional Dictionary Learning for Multimodal Imaging

Citation: Degraux, K.; Kamilov, U.; Boufounos, P.T.; Liu, D., "Online Convolutional Dictionary Learning for Multimodal Imaging", *IEEE International Conference on Image Processing (ICIP),* DOI: 10.1109/ICIP.2017.8296555, Sep. 2017.

Contacts: Petros T. Boufounos, Dehong Liu

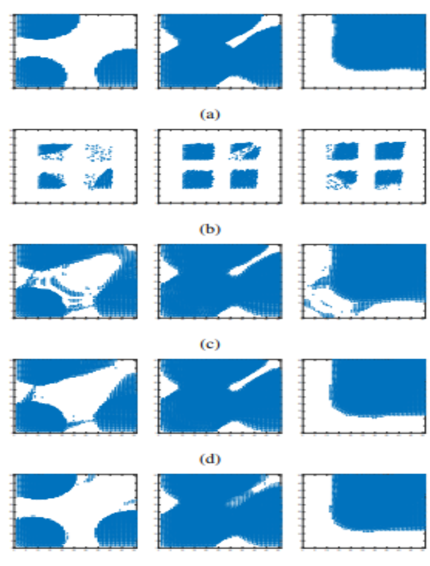


Computational imaging methods that can exploit multiple modalities have the potential to enhance the capabilities of traditional sensing systems. In this paper, we propose a new method that reconstructs multimodal images from their linear measurements by exploiting redundancies across different modalities. Our method combines a convolutional group-sparse representation of images with total variation (TV) regularization for high-quality multimodal imaging. We develop an online algorithm that enables the unsupervised learning of convolutional dictionaries on large-scale datasets that are typical in such applications. We illustrate the benefit of our approach in the context of joint intensity-depth imaging.

Crowd Flow Completion from Partial Spatial Observations Using Kernel DMD

Citation: Mansour, H.; Benosman, M.; Huroyan, V., "Crowd Flow Completion from Partial Spatial Observations Using Kernel DMD", *International Conference on Sampling Theory and Applications (SampTA)*, July 2017.

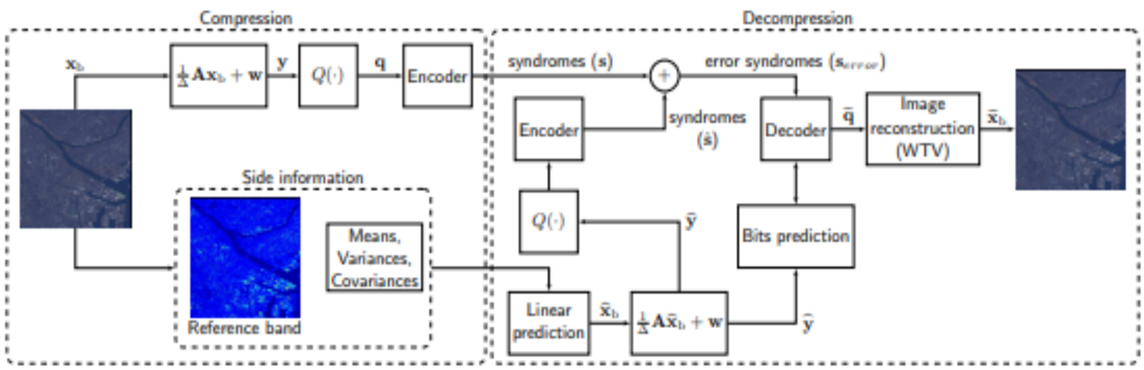
Contacts: Hassan Mansour, Mouhacine Benosman



In this paper, we address the problem of estimating the total flow of a crowd of pedestrians from spatially limited observations. Our approach relies on identifying a dynamical system regime that characterizes the observed flow in a limited spatial domain by solving for the modes and eigenvalues of the corresponding Koopman operator. We develop a framework where we first approximate the Koopman operator by computing the kernel dynamic mode decomposition (DMD) operator for different flow regimes using fully observed training data. We then pose flow completion as a least squares problem constrained by the one step evolution of the kernel DMD operator. We present numerical experiments with simulated pedestrian flows and demonstrate that the proposed approach succeeds in completing the flow from limited spatial observations.

Distributed Coding of Multispectral Images

Citation: Goukhshtein, M.; Boufounos, P.T.; Koike-Akino, T.; Draper, S.C., "Distributed Coding of Multispectral Images", *IEEE International Symposium on Information Theory (ISIT),* DOI: 10.1109/ISIT.2017.8007126, June 2017.
Contacts: Petros T. Boufounos, Toshiaki Koike-Akino



Compression of multi-spectral images is of great importance in an environment where resources such as computational power and memory are scarce. To that end, we propose a new extremely low-complexity encoding approach for compression of multispectral images, that shifts the complexity to the decoding. Our method combines principles from compressed sensing and distributed source coding. Specifically, the encoder compressively measures blocks of the band of interest and uses syndrome coding to encode the bitplanes of the measurements. The decoder has access to side information, which is used to predict the bitplanes and to decode them. The side information is also used to guide the reconstruction of the image from the decoded measurements. Our experimental results demonstrate significant improvement in the rate-distortion trade-off when compared to coding schemes with similar complexity.

Acceleration of FDTD-based Inverse Design Using a Neural Network Approach

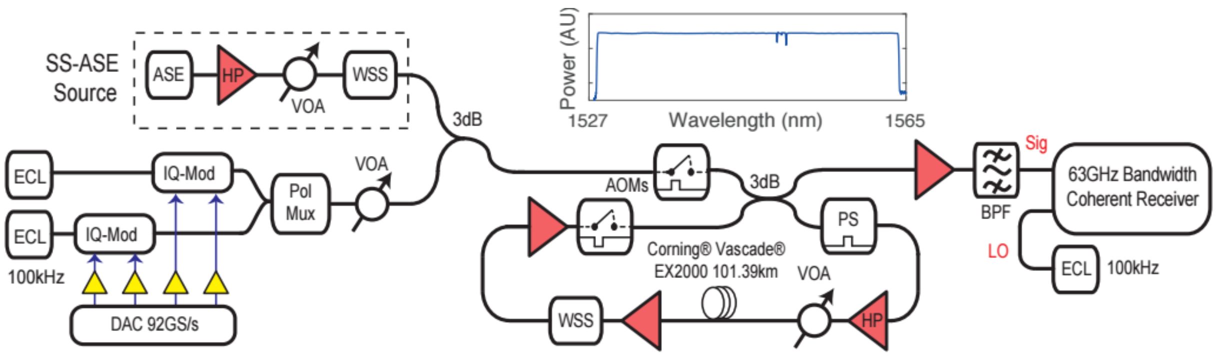
Citation: Kojima, K.; Wang, B.; Kamilov, U.; Koike-Akino, T.; Parsons, K., "Acceleration of FDTD-based Inverse Design Using a Neural Network Approach", *Integrated Photonics Research, Silicon and Nano Photonics (IPR)*, July 2017.
Contacts: Keisuke Kojima, Bingnan Wang, Toshiaki Koike-Akino, Kieran Parsons

Instead of using FDTD simulations for all the inverse design steps, we proposed to use neural network-based fitting to estimate the output of the FDTD simulations, and improve the design. We observed clear acceleration in the improvement of metric. wavelength spacing.

A Simplified Dual-Carrier DP-64QAM 1 Tb/s Transceiver

Citation: Millar, D.S.; Pajovic, M.; Koike-Akino, T.; Kojima, K.; Parsons, K., "A Simplified Dual-Carrier DP-64QAM 1 Tb/s Transceiver", *Optical Fiber Communication Conference and Exposition (OFC)*, DOI: 10.1364/OFC.2017.M3D.2, March 19, 2017.

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



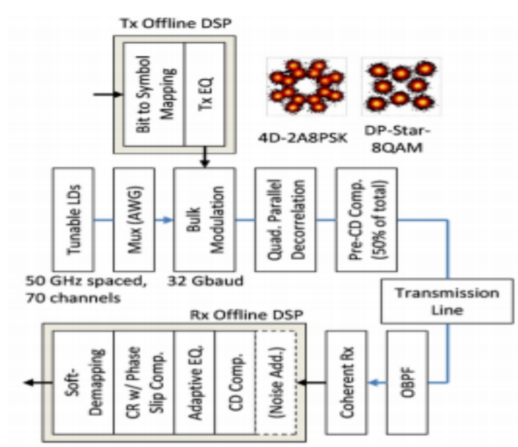
A 1 Tb/s net bitrate transceiver using a low complexity dual-carrier architecture with free running lasers and DP-64QAM, enabled by pilot-aided DSP and low-rate LDPC, is shown to achieve transmission over 400 km with 100 km amplifier spacing.

An Unsupervised Indoor Localization Method Based on Received Signal Strength (RSS)

Citation: Kojima, K.; Koike-Akino, T.; Millar, D.S.; Wang, B.; Pajovic, M.; Parsons, K.; Song, B.; Klamkin, J., "System and device technologies for coherent optical communications", *SPIE Photonics West*, DOI: 10.1117/12.2291869, vol. 10560, January 2018.

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

We review the recent advancement in the system and device technologies for coherent optical communications. One major topic is high-dimensional modulation, and in particular the nonlinearity-tolerant modulation format family, based on four-dimensional 2A8PSK. This family, covering 5, 6, 7 bits/4D symbol, outperforms most known corresponding modulation formats in the linear and nonlinear region. We also review our recent progress on forward error correction including polar codes, and monolithic narrow linewidth semiconductor lasers.

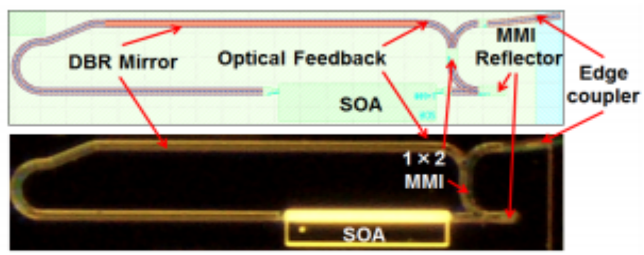


Frequency Noise Reduction of Integrated Laser Source with On-Chip Optical Feedback

Citation: Song, B.; Kojima, K.; Pina, S.; Koike-Akino, T.; Wang, B.; Klamkin, J., "Frequency Noise Reduction of Integrated Laser Source with On-Chip Optical Feedback", *Integrated Photonics Research, Silicon and Nano Photonics (IPR)*, DOI: 10.1364/IPRSN.2017.ITu1A.4, July 2017.

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

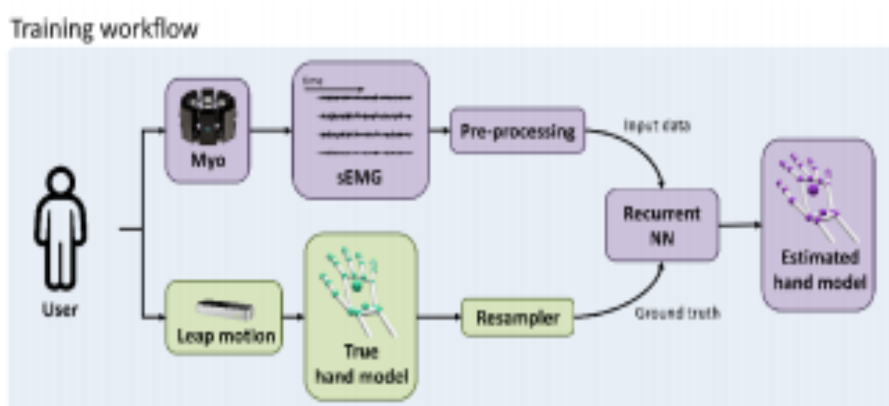
Integrated indium phosphide distributed-Bragg-reflector lasers with and without on-chip optical feedback are reported. The measured linewidth for the laser with coherent optical feedback is approximately 800 kHz, demonstrating an order of magnitude reduction.



Translating sEMG Signals to Continuous Hand Poses using Recurrent Neural Networks

Citation: Quivira, F.; Koike-Akino, T.; Wang, Y.; Erdogmus, D., "Translating sEMG Signals to Continuous Hand Poses using Recurrent Neural Networks", *IEEE Conference on Biomedical and Health Informatics (BHI)*, DOI: 10.1109/BHI.2018.8333395, January 2018.

Contacts: Toshiaki Koike-Akino, Yebin Wang



In this paper, we propose a hand pose estimation approach from low cost surface electromyogram (sEMG) signals using recurrent neural networks (RNN). We use the Leap Motion sensor to capture the hand joint kinematics and the Myo sensor to collect sEMG while the user is performing simple finger movements. We aim at building an accurate regression model that predicts hand joint kinematics from sEMG featur es. We use RNN with long short-term memory (LSTM) cells to account for the non-linear relationship between the two domains (sEMG and hand pose). Additionally, we add a Gaussian mixture model (GMM) to build a probabilistic model of hand pose given EMG data. We performed experiments across 7 users to test the performance of our approach. Our results show that for simple hand gestures such as finger flexion, the model is able to capture hand pose kinematics precisely.

Control & Dynamical Systems

The Control and Dynamical Systems Group has expertise in multivariable, nonlinear, optimal & model predictive control theory, nonlinear estimation, nonlinear dynamical systems, mechanical design, thermo-fluid system dynamics, laser processing and sensing, and rapid prototyping. The business drivers for this R&D program are twofold. First, control of mechanical and electrical 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 this group and other researchers in MERL's other 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, path planning and steering control for autonomous vehicles, more precise laser processing systems, smoother riding elevators, low-fuel mission plans for space probes and satellite station keeping. 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 indoor and outdoor airflow, traffic control, optimal transport, mixing in fluids and thermo-fluid systems dynamics, and the design of minimum-fuel trajectories for space probes, all of which exploit nonlinearity and chaos in highly creative and deeply mathematical ways.

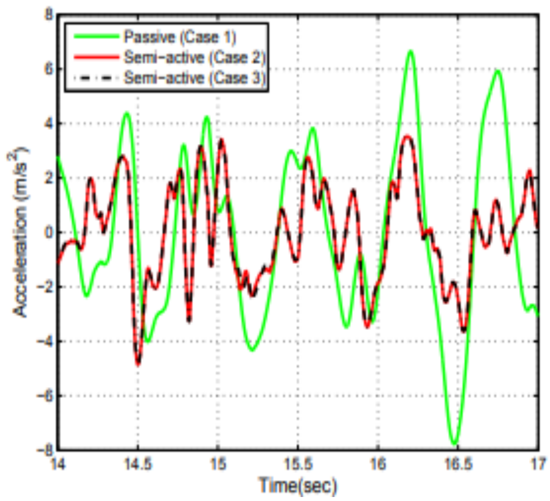
Recent Research

From acceleration-based semi-active vibration reduction control to functional observer design

Citation: Wang, Y.; Utsunomiya, K., “From acceleration-based semi-active vibration reduction control to functional observer design”, *Automatisierungstechnik*, DOI: 10.1515/auto-2017-0064, vol. 66, # 3, March 2018

Contacts: Yebin Wang

This work investigates a functional estimation problem for single input single output linear and nonlinear systems. It finds application in enabling accelerationbased semi-active control. Solvability of a linear functional estimation problem is studied from a geometric approach, where the functional dynamics are derived, decomposed, and transformed to expose structural properties. This approach is extended to solve a challenging nonlinear functional observer problem, combining with the exact error linearization. Existence conditions of nonlinear functional observers are established. Simulation verifies existence conditions and demonstrates the effectiveness of the proposed functional observer designs.

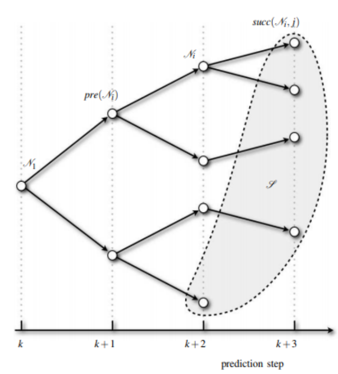


Stochastic Model Predictive Control

Citation: Mesbah, A.; Di Cairano, S.; Kolmanovsky, I.V., “Stochastic Model Predictive Control”, *Handbook of Model Predictive Control (book)*, February 2018.

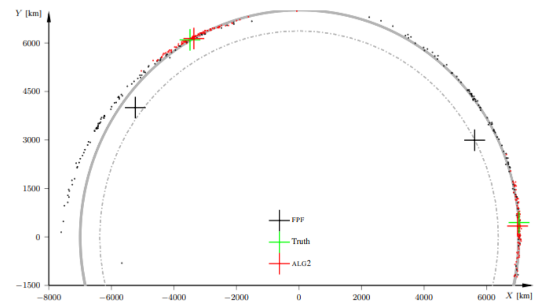
Contacts: Stefano Di Cairano

Stochastic Model Predictive Control (SMPC) accounts for model uncertainties and disturbances based on their statistical description. SMPC is synergistic with the well-established fields of stochastic modeling, stochastic optimization, and estimation. In particular, SMPC benefits from availability of already established stochastic models in many domains, existing stochastic optimization techniques, and well established stochastic estimation techniques. For instance, the effect of wind gusts on an aircraft can be modeled by stochastic von Karman and Dryden's models but no similar deterministic models appear to exist. Loads or failures in electrical power grids, prices of financial assets, weather (temperature, humidity, wind speed and directions), computational loads in data centers, demand for a product in marketing/supply chain management are frequently modeled stochastically thereby facilitating the application of the SMPC framework. A comprehensive overview of various approaches and applications of SMPC has been given in the article. Another overview article in Encyclopedia of Systems and Control is focused on tube SMPC approaches. This chapter provides a tutorial exposition of several SMPC approaches.



Feedback Particle Filter with Data-Driven Gain-Function Approximation

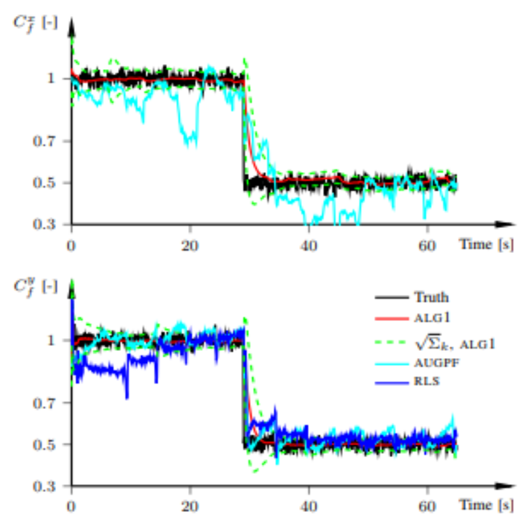
Citation: Berntorp, K.; Grover, P., “Feedback Particle Filter with Data-Driven Gain-Function Approximation”, *IEEE transactions on aerospace and electronic systems*, DOI: 10.1109/TAES.2018.2807559, February 2018.
Contacts: Karl Berntorp, Piyush Grover



This paper addresses the continuous-discrete time nonlinear filtering problem for stochastic dynamical systems using the feedback particle filter (FPF). The FPF updates each particle using feedback from the measurements, where the gain function that controls the particles is the solution of a Poisson equation. The main difficulty in the FPF is to approximate this solution using the particles that approximate the probability distribution. We develop a novel Galerkin-based method inspired by high-dimensional data-analysis techniques. Based on the time evolution of the particle cloud we determine basis functions for the gain function and compute values of it for each individual particle. Our method is completely adapted to the recorded history of the particles and the update of the particles do not require further intermediate approximations or assumptions.

Tire-Stiffness and Vehicle-State Estimation Based on Noise-Adaptive Particle Filtering

Citation: Berntorp, K.; Di Cairano, S., “Tire-Stiffness and Vehicle-State Estimation Based on Noise-Adaptive Particle Filtering”, *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/TCST.2018.2790397, February 2018.
Contacts: Karl Berntorp, Stefano Di Cairano

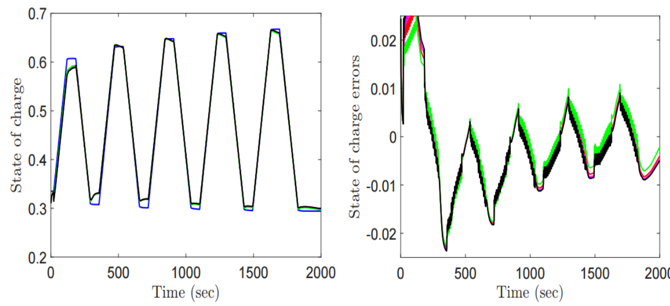


We present a novel approach to learning online the tire stiffness and vehicle state using only wheel-speed and inertial sensors. The deviations from nominal stiffness values are treated as a Gaussian disturbance acting on the vehicle. We formulate a Bayesian approach, in which we leverage particle filtering and the marginalization concept to estimate in a computationally efficient way the tire-stiffness parameters and the vehicle state. In the estimation model, the process and measurement noise are dependent on each other, and we present an efficient approach to account for the dependence. Our algorithm outperforms some previously reported approaches, both in terms of accuracy and robustness, and the results indicate significantly improved performance compared to a standard particle filter.

Revisiting the State of Charge Estimation for Lithium-Ion Batteries A Methodical Investigation of the EKF Approach

Citation: Wang, Y.; Fang, H.; Zhou, L.; Wada, T., “Revisiting the State of Charge Estimation for Lithium-Ion Batteries A Methodical Investigation of the EKF Approach”, *IEEE Control Systems Magazine*, October 2016.
Contacts: Yebin Wang

This article is devoted to nonlinear state and parameter estimation problems where the system is represented in the state-space framework. This article comprises of two parts where the first part provides a tutorial on prevailing nonlinear stochastic estimation techniques, and the second part presents a self-contained description of estimation problems and solutions in rechargeable Lithium-ion batteries.

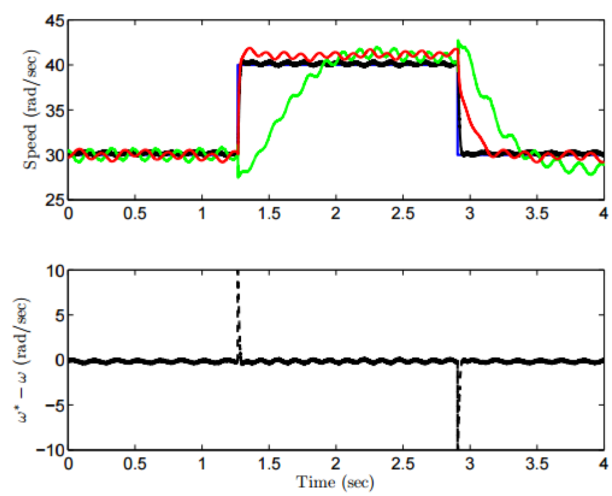


(a) (b)

High gain observer for speed-sensor-less motor drives: algorithm and experiments

Citation: Wang, Y.; Zhou, L.; Bortoff, S.A.; Satake, A.; Furutani, S., “High gain observer for speed-sensorless motor drives: algorithm and experiments”, *IEEE International Conference on Advanced Intelligent Mechatronics*, DOI: 10.1109/AIM.2016.7576921, pp. 1127 – 1132, July 2016.
Contacts: Yebin Wang, Scott A. Bortoff

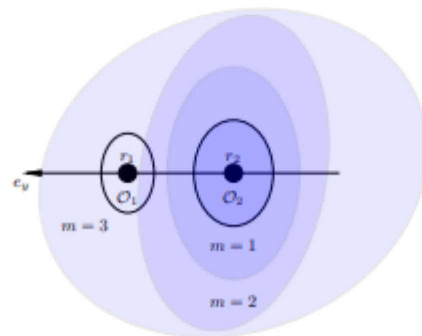
This paper considers the rotor speed and flux estimation for induction motors, which is one of the key problems in speed-sensorless motor drives. Existing approaches, e.g. adaptive, Kalman filter-based, and sliding mode observer, have limitations such as unnecessarily assuming the rotor speed as a constant parameter, failure to ensure convergence of estimation error dynamics, or conservative design. This paper proposes a nontriangular observable form-based estimation algorithm. This paper presents realizable observers to avoid transforming the induction motor model into the form. Advantages of the new estimation algorithm include guaranteed stability of estimation error dynamics, constructive observer design, ease of tuning, and improved speed estimation performance. Finally, experiments are conducted to demonstrate the effectiveness of the proposed estimation algorithm.



Automated Driving: Safe Motion Planning Using Positively Invariant Sets

Citation: Berntorp, K.; Weiss, A.; Danielson, C.; Di Cairano, S., “Automated Driving: Safe Motion Planning Using Positively Invariant Sets”, *International IEEE Conference on Intelligent Transportation Systems (ITSC)*, DOI: 10.1109/ITSC.2017.8317672, October 2017.

Contacts: Karl Berntorp, Avishai Weiss, Claus Danielson, Stefano Di Cairano,

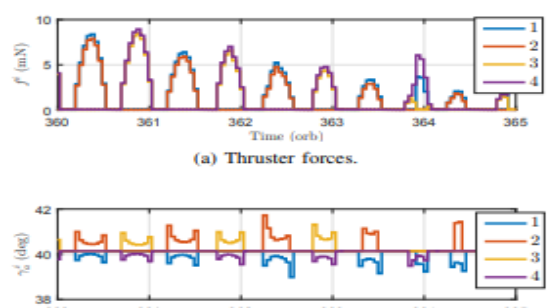


This paper develops a method for safe lane changes. We leverage feedback control and constraint-admissible positively invariant sets to guarantee collision-free closed-loop trajectory tracking. Starting from an initial state of the vehicle and obstacles in the region of interest, our method steers the vehicle to the desired lane while satisfying constraints associated with the future motion of the obstacles with respect to the vehicle. We connect the initial state with the desired lane using equilibrium points and associated positively invariant sets of the vehicle dynamics, where the positively invariant sets are used to guarantee safe transitions between the equilibrium points. An autonomous highway-driving example with a receding-horizon implementation shows that our method is capable of generating safe dynamically feasible trajectories in real-time while accounting for obstacles in the environment and modeling errors.

MPC for Coupled Station Keeping, Attitude Control, and Momentum Management of GEO Satellites using On-Off Electric Propulsion

Citation: Zlotnik, D.; Di Cairano, S.; Weiss, A., “MPC for Coupled Station Keeping, Attitude Control, and Momentum Management of GEO Satellites using On-Off Electric Propulsion”, *IEEE Conference on Control Technology and Applications*, DOI: 10.1109/CCTA.2017.8062723, August 2017.

Contacts: Stefano Di Cairano, Avishai Weiss



(a) Thruster forces.

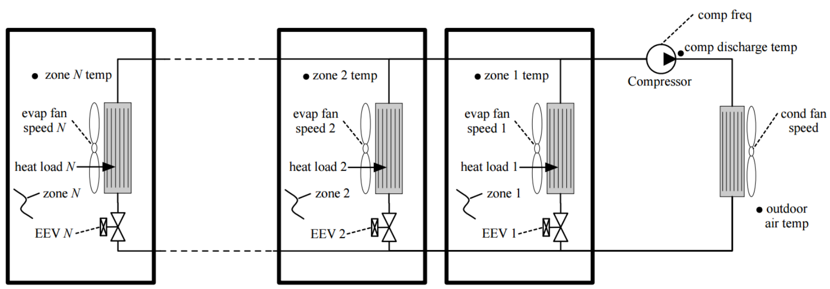
(b) Gimbal angles.

This paper develops a model predictive control (MPC) policy for simultaneous station keeping, attitude control, and momentum management of a nadir-pointing geostationary satellite equipped with three reaction wheels and four on-off electric thrusters mounted on two boom assemblies attached to the anti-nadir face of the satellite. A closed-loop pulse-width modulation (PWM) scheme is implemented in conjunction with the MPC policy in order to generate on-off commands to the thrusters. The MPC policy is shown to satisfy all station keeping and attitude constraints while managing stored momentum, enforcing thruster constraints, and minimizing required delta-v.

A Reconfigurable Plug-and-Play Model Predictive Controller for Multi-Evaporator Vapor Compression Systems

Citation: Zhou, J.; Burns, D.J.; Danielson, C.; Di Cairano, S., "A Reconfigurable Plug-and-Play Model Predictive Controller for Multi-Evaporator Vapor Compression Systems", *American Control Conference (ACC)*, DOI: 10.1109/ACC.2016.7525270, pp. 2358-2364, July 2016.
Contacts: Daniel J. Burns, Claus Danielson, Stefano Di Cairano

This paper presents a reconfigurable Plug-and-Play (PnP) Model Predictive Controller (MPC) for multi-evaporator vapor compression systems (VCSs) where individual evaporators are permitted to turn on or off.

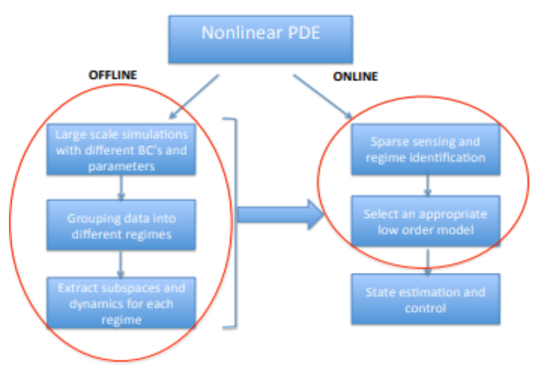


Results confirm that the reconfigurable PnP MPC maintains the same performance as a switched MPC approach in terms of room temperature reference tracking after zones are switched on, enforcement of critical machine constraints, and disturbance rejection. However, reconfigurable PnP MPC requires no extra tuning or controller design effort, and can be automatically synthesized from a single master controller design for any VCS operating mode.

Sparse sensing and DMD based identification of flow regimes and bifurcations in complex flows

Citation: Kramer, B.; Grover, P.; Boufounos, P.T.; Benosman, M.; Nabi, S., "Sparse sensing and DMD based identification of flow regimes and bifurcations in complex flows", *SIAM Journal on Applied Dynamical Systems*, DOI: 10.1137/15M104565X, vol. 16, iss. 2, pp. 1164-1196, July 2017.
Contacts: Piyush Grover, Petros T. Boufounos, Mouhacine Benosman, Saleh Nabi

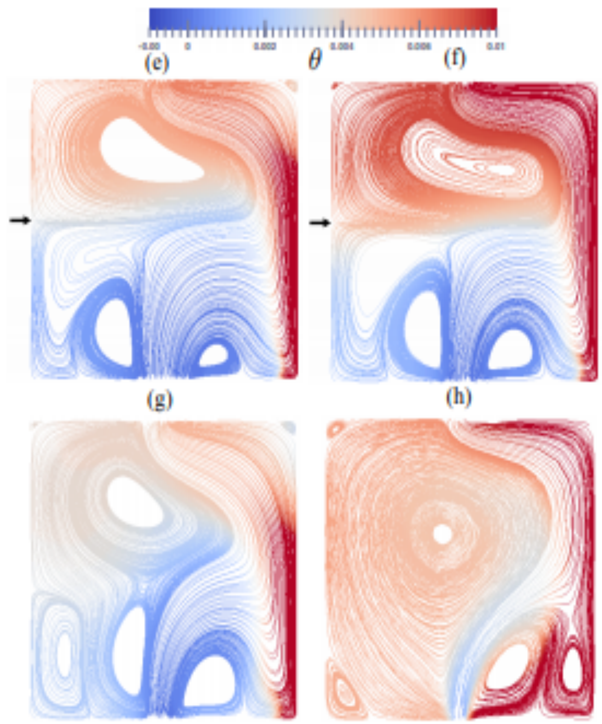
We present a sparse sensing framework based on Dynamic Mode Decomposition (DMD) to identify flow regimes and bifurcations in large-scale thermo-fluid systems. Motivated by real-time sensing and control of thermal-fluid flows in buildings and equipment, we apply this method to a Direct Numerical Simulation (DNS) data set of a 2D laterally heated cavity. The resulting flow solutions an be divided into several regimes, ranging from steady to chaotic flow. The DMD modes and eigenvalues capture the main temporal and spatial scales in the dynamics belonging to different regimes. This allows us to employ a short time-series of data from sensors, to more robustly classify flow regimes, particularly in the presence of measurement noise, which in turn can enable robust low-order modeling of flows for state estimation and control.



Adjoint-Based Optimization of Displacement Ventilation Flow

Citation: Nabi, S.; Grover, P.; Caulfield, C.C., “Adjoint-Based Optimization of Displacement Ventilation Flow”, *Building and Environment*, DOI: 10.1016/j.buildenv.2017.07.030, vol. 124, pp. 342-356, July 2017

Contacts: Saleh Nabi, Piyush Grover

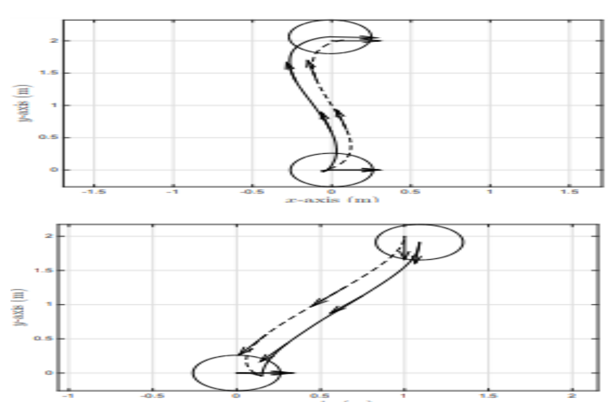


We demonstrate the use of the 'Direct-Adjoint-Looping method' for the identification of optimal buoyancy-driven ventilation flows governed by Boussinesq equations. We use the incompressible Reynolds averaged Navier-Stokes (RANS) equations, derive the corresponding adjoint equations and solve the resulting sensitivity equations with respect to inlet conditions. We focus on a displacement ventilation scenario with a steady plume due to a line source. Subject to an enthalpy flux constraint on the incoming flow, we identify boundary conditions leading to 'optimal' temperature distributions in the occupied zone. Our results show that depending on the scaled volume and momentum flux of the inlet flow, qualitatively different flow regimes may be obtained. The numerical optimal results agree with analytically obtained optimal inlet conditions available from classical plume theory in an 'intermediate' regime of strong stratification and two-layer flow.

Time-Optimal Solution for a Unicycle Path on SE(2) with a Penalty on Curvature

Citation: Halder, U.; Kalabic, U., “Time-Optimal Solution for a Unicycle Path on SE(2) with a Penalty on Curvature”, *IFAC World Congress*, July 2017.

Contacts: Uros Kalabic

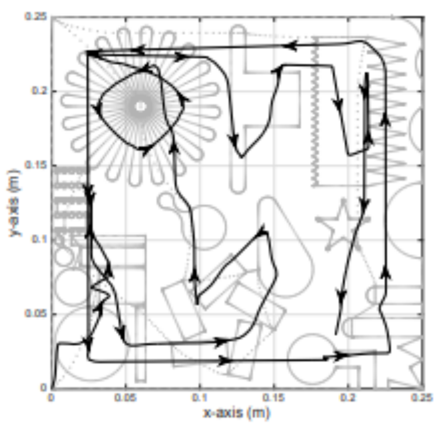


This work considers the problem of minimizing the path-curvature of a unicycle moving between two configurations in SE(2) with free final time. The problem is posed as an optimal control problem and the necessary conditions are derived using the Pontryagin Maximum Principle and Lie-Poisson reduction. Solutions are categorized into three cases corresponding to the value of the Casimir. A numerical solver for obtaining the optimal control is described.

Extended Command Governors for Constraint Enforcement in Dual-Stage Processing Machines

Citation: Kalabic, U.; Goldsmith, A.M.; Di Cairano, S., "Extended Command Governors for Constraint Enforcement in Dual-Stage Processing Machines", *American Control Conference (ACC)*, DOI: 10.23919/ACC.2017.7963278, May 2017

Contacts: Uros Kalabic, Abraham M. Goldsmith, Stefano Di Cairano

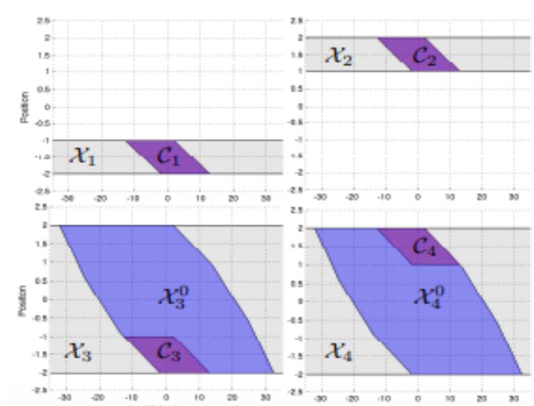


This manuscript presents a scheme for the constrained control of a dual-stage system used in precision manufacturing. The system consists of two stages, a fast and a slow stage, whose actuators have different bandwidths. The fast stage is primarily constrained in its range of operation, and the slow stage is primarily constrained in allowable velocity and acceleration. The constrained control is based on an extended command governor, which is a constraint-enforcement scheme used for closed-loop systems subject to state and control constraints. A method of dividing the motion between fast and slow stages is presented that is based on tracking a minimal-motion reference for the slow stage. The extended command governor scheme is modified to simultaneously ensure constraint-admissible tracking of the minimal-motion reference and machining of the desired manufacturing pattern.

Constraint Satisfaction for Switched Linear Systems with Restricted Dwell-Time

Citation: Danielson, C.; Bridgeman, L.; Di Cairano, S., "Constraint Satisfaction for Switched Linear Systems with Restricted Dwell-Time", *American Control Conference (ACC)*, DOI: 10.23919/ACC.2017.7963517, May 2017.

Contacts: Claus Danielson, Stefano Di Cairano



This paper considers the control of constrained linear systems with dynamics and constraints that change as a function of time according to an unknown exogenous switching signal that satisfies dwell-time restrictions. We characterize the set of initial conditions for which it is possible to guarantee constraint satisfaction for any admissible switching signal. We define the concept of control (positive) switch-invariant sets which are control (positive) invariant sets with the additional property that it is possible to transition between the control (positive) switch-invariant sets without violating constraints. It is possible to guarantee constraint satisfaction for a given initial condition if the control (positive) switch-invariant set of a mode can be reached from it within the dwell-time of that mode. An algorithm is presented for computing the maximal control (positive) switch-invariant sets. We demonstrate the theory developed in this paper on vehicle lane changing.

Multi-Physical Systems & Devices

Multi-Pyhisical Systems & Devices is a newly established group at MERL that develops core technology in multi-physical modeling & simulation as a foundation for other advanced technologies, such as signal processing, control, optimization, and artificial intelligence. We investigate mathematical formulations of multi-physical dynamics, accurate models of complex systems via advanced tools, fundamental principles and applied physics research, and model-based design and optimization processes.

The "Systems" research focuses on the following areas: the development and application of new tools to model and simulate complex, heterogeneous systems; the creation of new multi-physical system designs (architectures) and performance metrics; the invention of new optimal control, coordinating control, and estimation algorithms; and the use of collaborative design tools and processes for future products. Target applications include model-based HVAC design, control and optimization; advanced assembly lines in factories; and digital twin systems for zero-energy buildings.

The "Devices" work emphasizes highly reliable wideband power amplifier technologies and semiconductor devices; motor modeling and fault detection; electro-magnetic analysis for non-contact sensing; first-principles analysis of condensed matter physics for new material design, magnetic resonance imaging, and magnetic particle imaging.

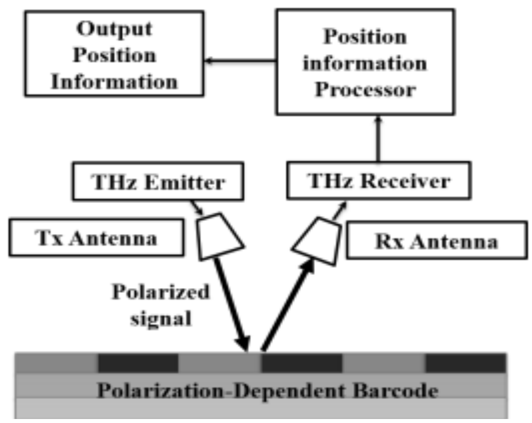
Recent Research

Metamaterial Absorber for THz Polarimetric Sensing

Citation: Wang, B.; Sadeqi, A.; Ma, R.; Wang, P.; Tsujita, W.; Sadamoto, K.; Sawa, Y.; Rezaei Nejad, H.; Sonkusale, S.; Wang, C.; Kim, M.; Han, R., "Metamaterial Absorber for THz Polarimetric Sensing", *SPIE Photonics West*, DOI: 10.1117/12.2293122, Vol. 10531, February 2018

Contacts: Bingnan Wang, Rui Ma, Pu (Perry)

THz encoders have distinct advantages for position sensing compared with other types of encoders, such as those based on optical and inductive sensors. A polarization-dependent metamaterial absorber reflects one polarization while absorbs the other, which makes it an ideal building block for the barcode of a THz encoder system. In this paper, we present the design, fabrication, and experiments of a THz polarization-dependent metamaterial absorber, and its application to a polarimetric sensing system.

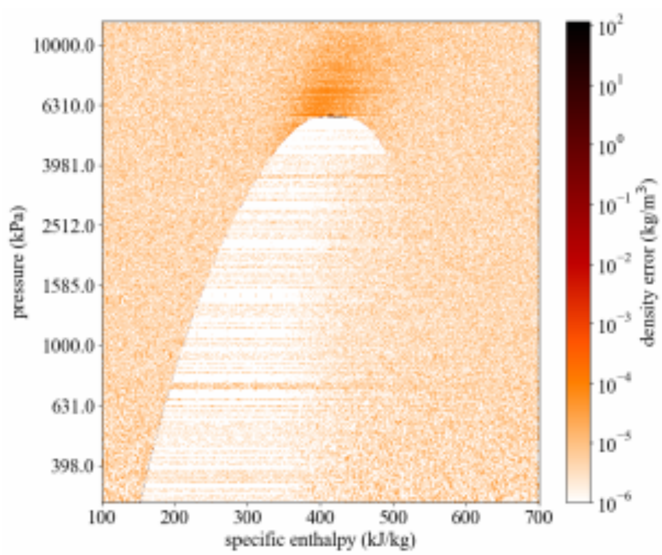


Approximation of Refrigerant Properties for Dynamic Vapor Compression Cycle Models

Citation: Laughman, C.R.; Van, C., "Approximation of Refrigerant Properties for Dynamic Vapor Compression Cycle Models", *MATHMOD*, February 2018.

Contacts: Christopher R. Laughman

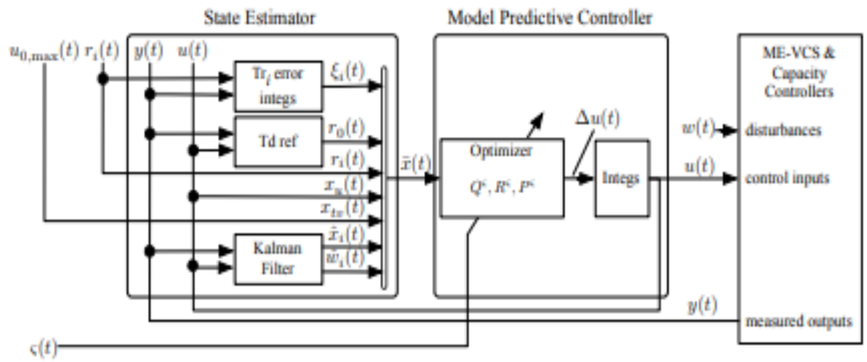
Thermophysical refrigerant property models play an essential role in dynamic models of vapor compression cycles, due to their highly nonlinear behavior, their coupling with many phenomena of interest, and the number of property computations required to simulate a cycle. As conventional iterative calculation methods are often too slow to be practically useful for such simulations, we compare two different approximation approaches, including one method that incorporates approximations of the liquid and vapor saturation lines, and another which approximates the entire property surface over a given domain. These methods are implemented in Modelica and are demonstrated to successfully describe the nonlinear behavior of the refrigerant R-32 in a computationally and memory-efficient manner.



Model Predictive Control of Vapor Compression Systems

Citation: Burns, D.J.; Danielson, C.; Di Cairano, S.; Laughman, C.R.; Bortoff, S.A., "Model Predictive Control of Vapor Compression Systems", *Intelligent Building Control*, February 2018.

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

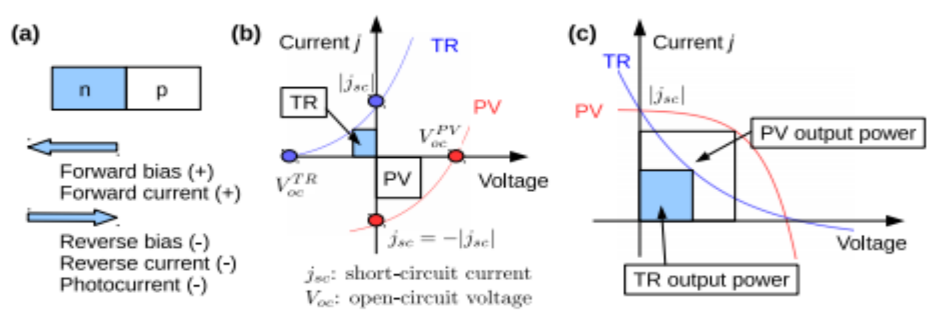


A model predictive controller is designed for a multizone vapor compression system. Controller requirements representing desired performance of production-scale equipment are provided and include baseline requirements common in control literature (constraint enforcement, reference tracking, disturbance rejection) and also extended requirements necessary for commercial application (selectively deactivating zones, implementable on embedded processors with limited memory/computation, compatibility with demand response events). A controller architecture is presented based on model predictive control to meet the requirements.

Performance Comparison Between Photovoltaic and Thermo-radiative Devices

Citation: Lin, C.; Wang, B.; Teo, K.H.; Zhang, Z., "Performance comparison between photovoltaic and thermos-radiative devices", *Journal of Applied Physics*, DOI: 10.1063/1.5004651, Vol. 122, No. 24, December 2017

Contacts: Chungwei Lin, Bingnan Wang, Koon Hoo Teo

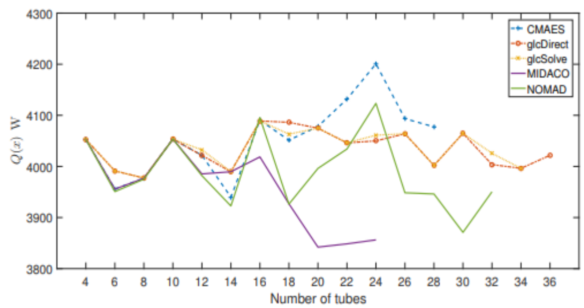


Photovoltaic (PV) and thermos-radiative (TR) devices are power generators that use the radiative energy transfer between a hot and a cold reservoir. For PV devices, the semiconductor at the cold side (PV cell) generates electric power; for TR devices, the semiconductor at the hot side (TR cell) generates electric power. In this work, we compare the performance of the photovoltaic and thermo-radiative devices, with and without non-radiative processes. Without non-radiative processes, PV devices generally produce larger output powers than TR devices. However, when non-radiative processes become important, the TR can outperform the PV devices.

Optimization of Circuitry Arrangements for Heat Exchangers Using Derivative-Free Optimization

Citation: Ploskas, N.; Laughman, C.R.; Raghunathan, A.U.; Sahinidis, N.V., "Optimization of circuitry arrangements for heat exchangers using derivative-free optimization", *Chemical Engineering Research and Design*, DOI: 10.1016/j.cherd.2017.05.015, October 2017.

Contacts: Christopher R. Laughman, Arvind Raghunathan

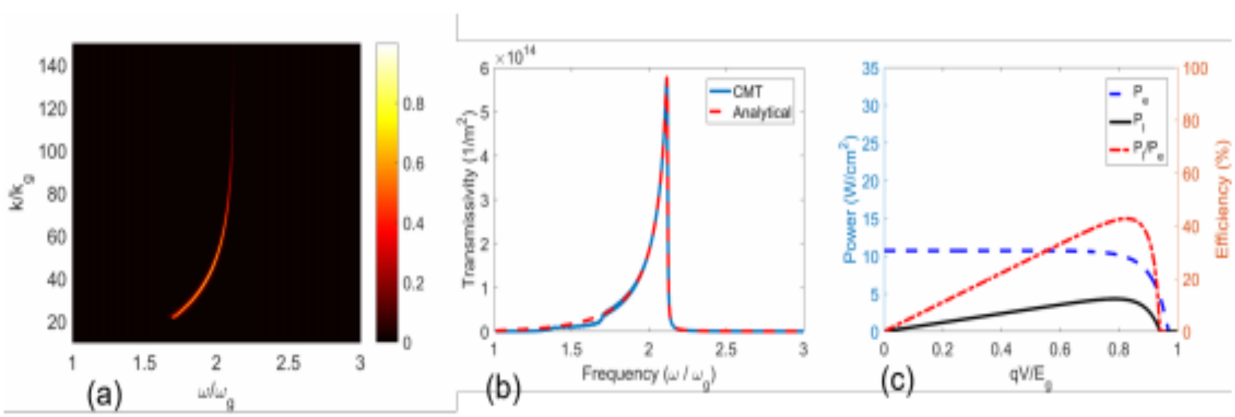


In this paper, we formulate refrigerant circuitry design as a binary constrained optimization problem. We use CoilDesigner, a simulation and design tool of air to refrigerant heat exchangers, in order to simulate the performance of different refrigerant circuitry designs and use Derivative-free optimization (DFO) algorithms. We compare four mixed-integer constrained DFO solvers and one box-bounded DFO solver and evaluate their ability to solve a difficult industrially relevant problem. We demonstrate that the proposed formulation is suitable for optimizing the circuitry configuration of heat exchangers.

Near-Field Thermophotovoltaic System Design and Calculation Based on Coupled-Mode Analysis

Citation: Wang, B.; Lin, C.; Teo, K.H., "Near-Field Thermophotovoltaic System Design and Calculation based on Coupled-Mode Analysis", *Journal of Photonics for Energy*, DOI: 10.1117/1.JPE.7.044501, Vol. 3, October 2017.

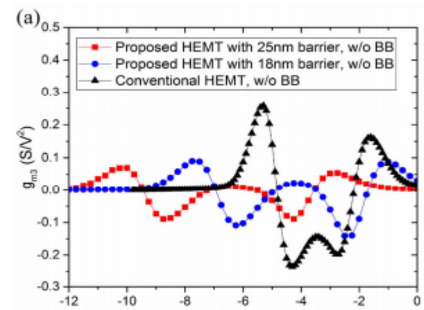
Contacts: Bingnan Wang, Chungwei Lin, Koon Hoo Teo



The coupling of resonant modes between surfaces is important in near-field heat transfer and near-field thermophotovoltaic (TPV) systems. Recently, coupled-mode theory (CMT) has been developed for the analysis and optimal design of TPV systems. We use CMT to analyze the "emitter-vacuum-PV cell" configuration, and quantitatively show that how the emitter of a nanostructure is designed can drastically improves the near-field TPV device performance.

Simulation of GaN HEMT with Wide-Linear-Range Transconductance

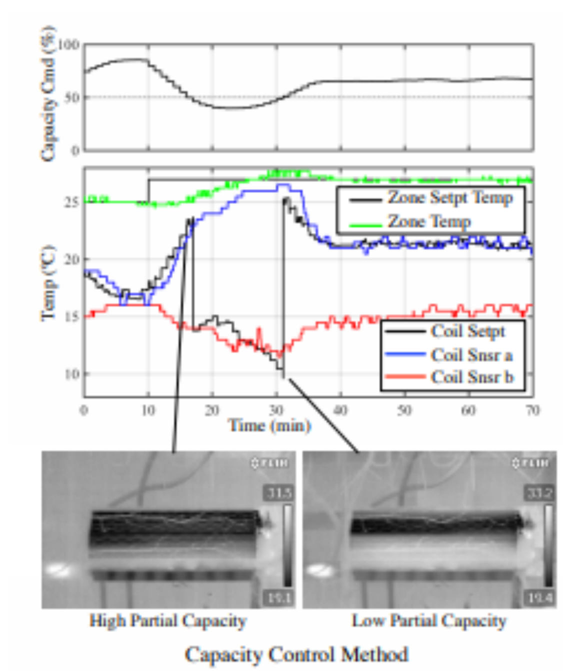
Citation: Teo, K.H.; Shi, J., "Simulation of GaN HEMT with Wide-Linear-Range Transconductance", *IEEE Electron Devices and Solid-State Circuits Conference*, DOI: 10.1109/EDSSC.2017.8126442, October 2017.
Contacts: Koon Hoo Teo



This paper presents a simulation study of how to achieve wide-linear-range transconductance of T-gate GaN HEMTs by introducing a o-doped layer and a p-GaN back barrier. With optimized o-doping density and location, the transconductance (gm) and current gain cutoff frequencies (fr) are ultra-flat and remain close to their peak values over a wide range of gate/source voltages (Vgs). In addition, a smaller absolute gm3 (third-order derivative of the Ids-Vgs curve) over a wide range of Vgs is obtained in proposed HEMTs. These features are valuable in designing highly linear RF AlGaN/GaN HEMTs.

Exploiting Refrigerant Distribution for Predictive Control of Multi-Evaporator Vapor Compression Systems

Citation: Burns, D.J.; Bortoff, S.A., "Exploiting Refrigerant Distribution for Predictive Control of Multi-Evaporator Vapor Compression Systems", *IEEE Conference on Control Technology and Applications (CCTA)*, DOI: 10.1109/CCTA.2017.8062509, August 2017.
Contacts: Daniel J. Burns, Scott A. Bortoff

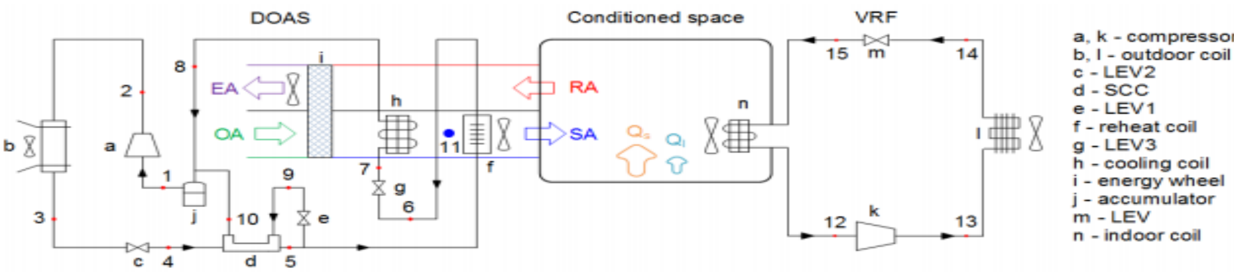


In this paper, we describe the following empirical property exploited for control: as the inlet valve position is decreased, refrigerant mass flow rate entering the heat exchanger is reduced, and for some flow rates, refrigerant is shown to preferentially flow in some paths more than others, causing maldistribution. This uneven refrigerant distribution is repeatable, reduces the capacity in a continuous manner and can be exploited with feedback controllers to regulate the perzone cooling. A controller is designed to provide stability and robustness to per-zone conditions and setpoints for this controller that relate per-path superheat temperature to overall evaporator capacity is created in such a way as to be robust to changes in local zone temperatures and the overall system evaporating temperature. This strategy provides zone decoupling and ultimately creates a virtual control input for a model predictive controller.

Simulation and Optimization of Integrated Air-Conditioning and Ventilation Systems

Citation: Laughman, C.R.; Qiao, H.; Bortoff, S.A.; Burns, D.J., “Simulation and Optimization of Integrated Air-Conditioning and Ventilation Systems”, *International Building Performance Simulation Association Conference*, August 2017.

Contacts: Christopher R. Laughman, Hongtao Qiao, Scott A. Bortoff, Daniel J. Burns

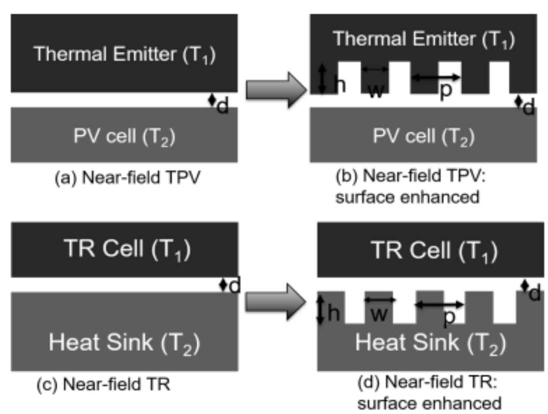


One promising path for reducing the power consumption and improving the performance of building HVAC systems involves the coordinated design and operation of individual subsystems. We propose a physical model-based approach for evaluating, optimizing, and designing control algorithms for an HVAC system consisting of a dedicated outdoor air system (DOAS) and a variable refrigerant flow (VRF) system serving a large occupied space. We demonstrate that the energy consumption can be reduced by 15%.

Nanostructure Enhanced Near-Field Radiative Heat Transfer and Designs for Energy Conversion Devices

Citation: Wang, B.; Lin, C.; Teo, K.H., “Nanostructure enhanced near-field radiative heat transfer and designs for energy conversion devices”, *SPIE Optics and Photonics*, DOI: 10.1109/MWSCAS.2017.8053131, August 2017.

Contacts: Bingnan Wang, Chungwei Lin, Koon Hoo Teo

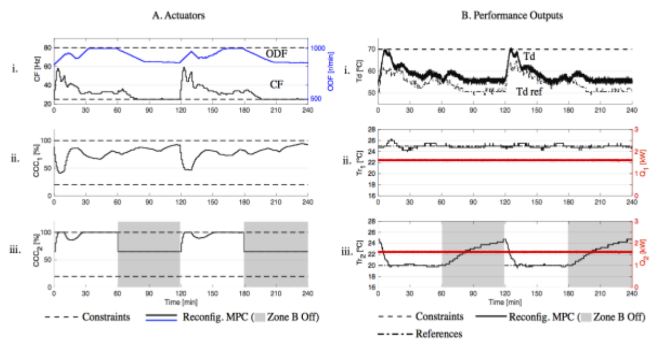


Near-field radiative heat transfer can exceed the blackbody limit, and this property has been explored toward energy transfer and conversion applications, such as thermophtovoltaic (TPV) devices, radiative cooling devices, and thermoradiative (TR) devices. The coupling of resonant modes between two surfaces is important in near-field heat transfer and near-field TPV and TR systems. It was shown that the coupling of resonant modes enhances the transmissivity between two coupled objects, which further determines the radiative heat transfer and energy conversion. We show that the nanostrctured designs significantly improves near-field radiative power transfer, and electric power output for a TR system.

Reconfigurable Model Predictive Control for Multi-Evaporator Vapor Compression Systems

Citation: Burns, D.J.; Danielson, C.; Zhou, J.; Di Cairano, S., “Reconfigurable Model Predictive Control for Multi-Evaporator Vapor Compression Systems”, *IEEE Transactions on Control Systems Technology*, June 2017.

Contacts: Daniel J. Burns, Claus Danielson, Stefano Di Cairano

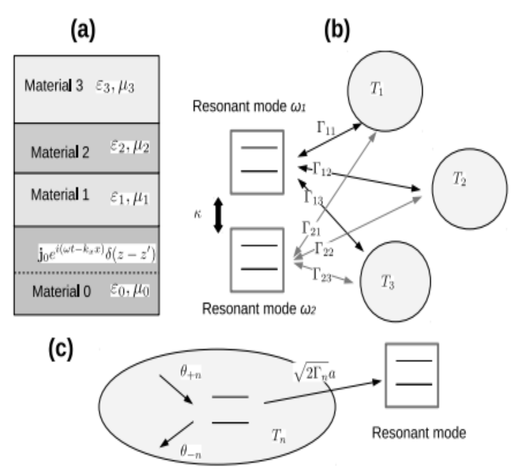


We demonstrate the use of the 'Direct-Adjoint-Looping method' for the identification of optimal buoyancy-driven ventilation flows governed by Boussinesq equations. We use the incompressible Reynolds-averaged Navier-Stokes (RANS) equations, derive the corresponding adjoint equations and solve the resulting sensitivity equations with respect to inlet conditions. We focus on a displacement ventilation scenario with a steady plume due to a line source. Our results show that depending on the scaled volume and momentum flux of the inlet flow, qualitatively different flow regimes may be obtained.

Application of Coupled Mode Theory on Radiative Heat Transfer Between Layered Lorentz Materials

Citation: Lin, C.; Wang, B.; Teo, K.H., “Application of coupled mode theory on radiative heat transfer between layered Lorentz materials”, *Journal of Applied Physics*, DOI: 10.1063/1.4983021, Vol. 121, No. 18, May 2017.

Contacts: Chungwei Lin, Bingnan Wang, Koon Hoo Teo

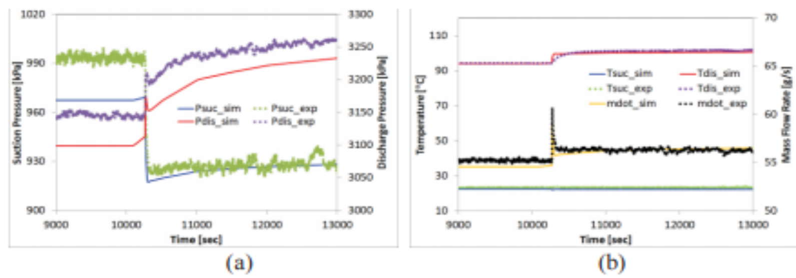


Coupled mode theory (CMT) provides a simple and clear framework to analyze the radiation energy exchange between reservoirs. We apply CMT to analyze the radiative heat transfer between layered Lorentz materials, whose dielectric functions can be approximated by the Lorentz oscillator model. By comparing the transmissivity computed by the exact solution to that computed by CMT, we find CMT generally gives a good approximation for this class of materials. The biggest advantage of CMT analysis, in our opinion, is that only the (complex) resonant energies are needed to obtain the radiation energy transfer; the knowledge of spatial profile of resonances is not required. Several issues, including how to choose the resonant modes, what these modes represent, and the limitation of this method, are discussed. Finally, we also apply CMT method to the electronic systems, demonstrating the generality of this formalism.

Dynamic Characteristics of an R-410A Multi-Split Variable Refrigerant Flow Air-Conditioning System

Citation: Qiao, Hongtao; Laughman, C.R.; Burns, D.J.; Bortoff, S.A., "Dynamic Characteristics of an R-410A Multi-split Variable Refrigerant Flow Air-conditioning System", *12th IEA Heat Pump Conference*, May 2017

Contacts: Hongtao Qiao, Christopher R. Laughman, Daniel J. Burns, Scott A. Bortoff

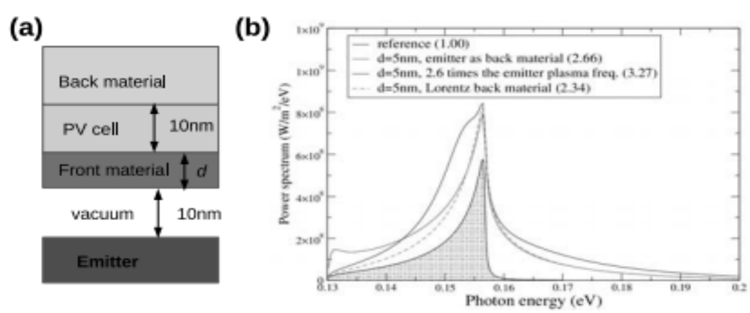


There is a dearth of comprehensive studies that explore the complex multivariable dynamic behavior of air-source VRF systems with commercially prevalent architectures. This paper describes a first-principles model of such an air-conditioner with four indoor units that is validated against experimental data. This validated simulation model is then used to study the dynamic system response subject to various sets of conditions, including variations in the compressor speed, fan speeds, and valve openings.

Application of Impedance Matching for Enhanced Transmitted Power in a Thermophotovoltaic System

Citation: Lin, C.; Wang, B.; Teo, K.H.; Bandaru, P.R., "Application of impedance matching for enhanced transmitted power in a thermophotovoltaic system", *Physical Review Applied*, DOI: 10.1103/PhysRevApplied.7.034003, Vol. 7, No. 3, April 2017.

Contacts: Chungwei Lin, Bingnan Wang, Koon Hoo Teo



Based on the impedance matching condition, we propose a few configurations that can greatly enhance radiation power transfer from the emitter to the photovoltaic (PV) cell for a near-field based thermophotovoltaic (TPV) system. In addition to the emitter and PV cell, these configurations involve the use of additional materials that support resonant modes, such as a metallic material whose dielectric function can be described by a Drude model, or a dielectric material whose dielectric function can be approximated by a Lorentz oscillator model. We show that by coating the PV cell both on the front and back sides with Lorentz materials, the transferred power can be 2.5 times larger than that without any decorations. When Drude metals are included in the configuration, the optimal transferred power can be 3 times larger than the system without additional materials. We find the key to enhance transmitted power is to place a thin layer of Drude/Lorentz material on the front side (facing the emitter) of the PV cell.

Algorithms

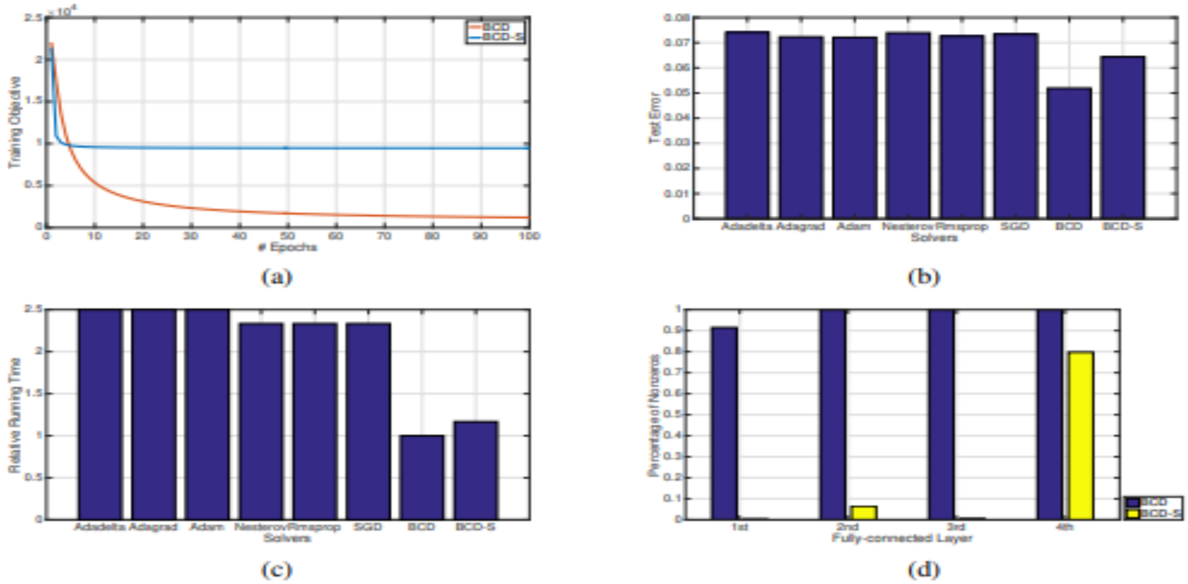
Researchers in the Algorithms group at MERL develop solution methods for optimization problems involving very large numbers of variables or real-time computing, particularly in settings where current methods are not viable. Our results can open new business opportunities where there are no competitive technologies. Much of the group's work involves graph-based optimizations, where the graph is a representation of the problem and associated computational constraints such as the dataflow of a parallel computer. This meshes with and helps build MERL's expertise in fields and technologies such as machine learning, computer vision, dynamic programming, convex optimization, computational mathematics, control, physics, and signal processing. Another main research theme involves adaptively-sampled distance fields (ADFs), an efficient representation for shapes of any dimension. ADFs have distinct advantages over alternative forms, including superior font and graphical rendering for digital displays.

Recent Research

Convergent Block Coordinate Descent for Training Tikhonov Regularized Deep Neural Networks

Citation: Ziming, Z.; Brand, M.E., "Convergent Block Coordinate Descent for Training Tikhonov Regularized Deep Neural Networks", *Advances in Neural Information Processing Systems (NIPS),* December 2017.

Contact: Ziming Zhang, Matthew E. Brand



By lifting the ReLU function into a higher dimensional space, we develop a smooth multi-convex formulation for training feed-forward deep neural networks (DNNs). This allows us to develop a block coordinate descent (BCD) training algorithm consisting of a sequence of numerically well-behaved convex optimizations. Using ideas from proximal point methods in convex analysis, we prove that this BCD algorithm will converge globally to a stationary point with R-linear convergence rate of order one. In experiments with the MNIST database, DNNs trained with this BCD algorithm consistently yielded better test-set error rates than identical DNN architectures trained via all the stochastic gradient descent (SGD) variants in the Caffe toolbox.

Rapid and accurate dose computation and optimization for IMPT

Citation: Sullivan, A.; Brand, M.E., "Rapid and accurate dose computation and optimization for IMPT", *Particle Theory Co-Operative Group*, May 2016

Contacts: Alan Sullivan, Matthew E. Brand

The speed of IMPT dose optimization is the key factor limiting the rate of treatment plan generation. Long optimization times have the effect of forcing dosimetrists to compromise due to time limitations and potentially select lower quality plans. The speed of dose optimization is determined both by the optimization algorithm itself and by the underlying dose computation algorithm.

Preconditioning for Continuation Model Predictive Control

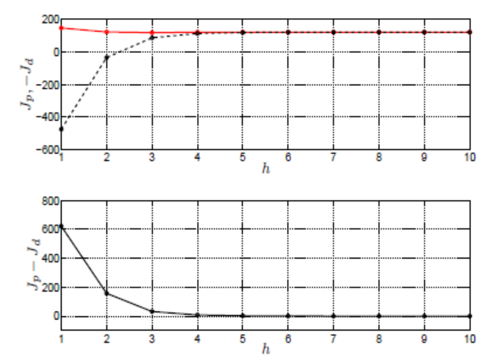
Citation: Knyazev, A.; Malyshev, A., "Preconditioning for Continuation Model Predictive Control", IFAC Conference on Nonlinear Model Predictive Control, DOI: 10.1016/j.ifacol.2015.11.282,Vol. 48, pp.191-196, September 2015
Contact: Andrew Knyazev

Model predictive control (MPC) anticipates future events to take appropriate control actions. Nonlinear MPC (NMPC) deals with nonlinear models and/or constraints. A Continuation/GMRES Method for NMPC, suggested by T. Ohtsuka in 2004, uses the GMRES iterative algorithm to solve a forward difference approximation Ax = b of the original NMPC equations on every time step. We have previously proposed accelerating the GMRES and MINRES convergence by preconditioning the coefficient matrix A. We now suggest simplifying the construction of the preconditioner, by approximately solving a forward recursion for the state and a backward recursion for the costate, or simply reusing previously computed solutions.

$$F[U,x,t] = \begin{bmatrix} \frac{\partial H^T}{\partial u}(\tau_0, x_0, \lambda_1, u_0, \mu_0, p)\Delta\tau \\ \vdots \\ \frac{\partial H^T}{\partial u}(\tau_i, x_i, \lambda_{i+1}, u_i, \mu_i, p)\Delta\tau \\ \vdots \\ \frac{\partial H^T}{\partial u}(\tau_{N-1}, x_{N-1}, \lambda_N, u_{N-1}, \mu_{N-1}, p)\Delta\tau \\ C(\tau_0, x_0, u_0, p)\Delta\tau \\ \vdots \\ C(\tau_i, x_i, u_i, p)\Delta\tau \\ \vdots \\ C(\tau_{N-1}, x_{N-1}, u_{N-1}, p)\Delta\tau \\ \psi(x_N, p) \\ \frac{\partial \phi^T}{\partial p}(x_N, p) + \frac{\partial \psi^T}{\partial p}(x_N, p)\nu \\ + \sum_{i=0}^{N-1} \frac{\partial H^T}{\partial p}(\tau_i, x_i, \lambda_{i+1}, u_i, \mu_i, p)\Delta\tau \end{bmatrix}.$$

Projection-free Parallel Quadratic Programming for Linear Model Predictive Control

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



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

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 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.

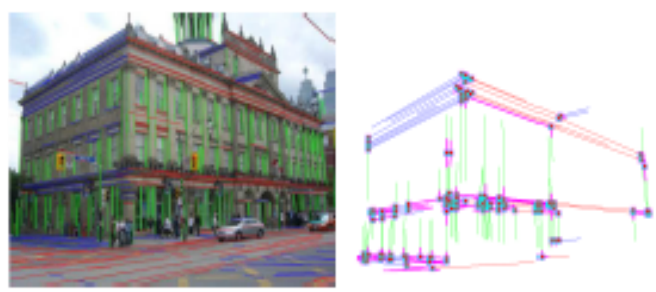
(a) 4 of 30 low-res images (b) reconstructed high-res image

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: 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.



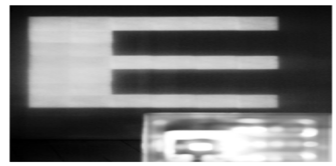
(a) (b)

(c) (d)

Sharp images from freeform optics and extended light sources

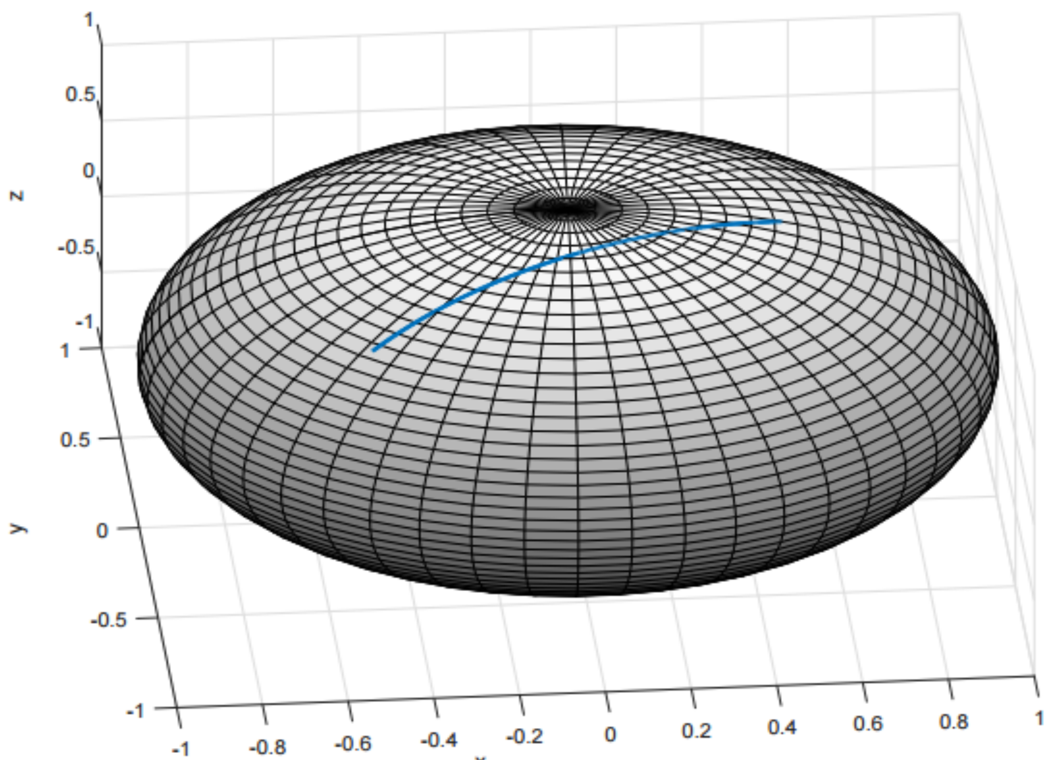
Citation: Brand, M.E., Aksoylar, A., "Sharp images from freeform optics and extended light sources", *OSA Frontiers in Optics*, DOI: 10.1364/FIO.2016.FW5H.2, ISBN: 978-1-943580-19-4, October 2016.
Contact: Matthew Brand

We introduce a class of pictorial irradiance patterns that freeform optics can render sharply despite the blurring effect of extended light sources; show how to solve for the freeform geometry; and demonstrate a fabricated lens.



Least squares dynamics in Newton-Krylov Model Predictive Control

Citation: Knyazev, A., Malyshev, A., "Least squares dynamics in Newton-Krylov Model Predictive Control"
Contact: Andrew Knyazev

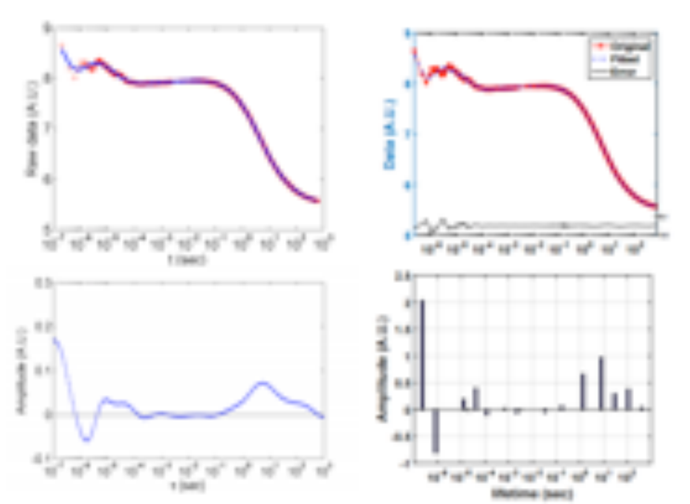


Newton-Krylov methods for nonlinear Model Predictive Control were pioneered by T. Ohtsuka under the name "C/GMRES". Ohtsuka eliminates a system state over the horizon from Karush-Kuhn-Tucker stationarity conditions of a Lagrangian using equations of system dynamics. We propose instead using least squares to fit the state to the dynamics and some constraints on the state, if they are inconsistent. Correspondingly modified Newton-Krylov methods are described. Numerical tests demonstrate workability of our modification.

Multi-exponential Lifetime Extraction in Time-logarithmic Scale

Citation: Knyazev, A.; Gao, Q.; Teo, K.H., "Multi-exponential Lifetime Extraction in Time-logarithmic Scale", *Industrial Conference on Data Mining (ICDM)*, DOI: 10.1007/978-3-319-41561-1_21, vol. 9728, pp. 282-296, July 2016

Contact: Andrew Knyazev, Koon H. Teo

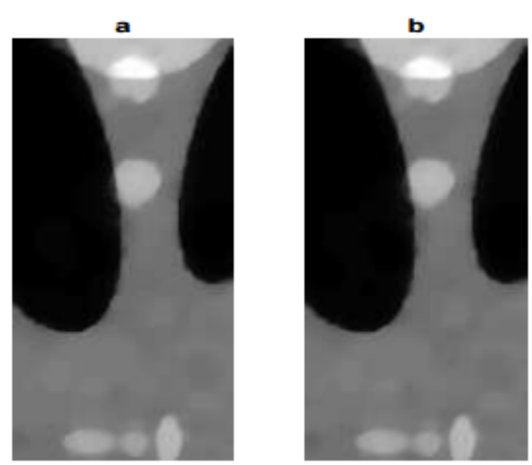


Methods are proposed for estimating real lifetimes and corresponding coefficients from real-valued measurement data in logarithmic scale, where the data are multi-exponential, i.e. represented by linear combinations of decaying exponential functions with various lifetimes. Initial approximations of lifetimes are obtained as peaks of the first derivative of the data, where the first derivative can, e.g, be calculated in the spectral domain using the cosine Fourier transform. The coefficients corresponding to lifetimes are then estimated using the linear least squares fitting. Finally, all the coefficients and the lifetimes are optimized using the values previously obtained as initial approximations in the non-linear least squares fitting.

Accelerated Graph-based Nonlinear Denoising Filters

Citation: Knyazev, A.; Malyshev, A., "Accelerated Graph-based Nonlinear Denoising Filters", *International Conference on Computational Science (ICCS)*, DOI: 10.1016/j.procs.2016.05.348, vol. 80, pp. 607-616, June 2016.

Contact: Andrew Knyazev



Denoising filters, such as bilateral, guided, and total variation filters, applied to images on general graphs may require repeated application if noise is not small enough. We formulate two acceleration techniques of the resulting iterations: conjugate gradient method and Nesterov's acceleration. We numerically show efficiency of the accelerated nonlinear filters for image denoising and demonstrate 2-12 times speed-up, i.e., the acceleration techniques reduce the number of iterations required to reach a given peak signal-to-noise ratio (PSNR) by the above indicated factor of 2-12.