Automotive Research Center

24th Annual ARC Program Review

May 16-17, 2018 Ann Arbor, MI

Day 1 Agenda
Wednesday May 16

(click here or scroll down for Day 2 program)

Francois-Xavier Bagnoud Building (FXB)
University of Michigan (North Campus)
1320 Beal Ave, Ann Arbor, MI 48109

9:00 **Check-in and Continental Breakfast**

9:30 **Welcome & Opening Remarks**
Prof. Bogdan Epureanu
Director, Automotive Research Center

Dr. David Gorsich
Chief Scientist, U.S. Army TARDEC

9:50 **Keynote**:
Dr. Chris Gerdes
Professor of Mechanical Engineering, Stanford University
Director, Center for Automotive Research at Stanford (CARS)

10:35 **Break**

10:50 **Technical Session 1** (matrix of parallel sessions)

1A: Algorithms & Intelligence

1B: Electrification & Thermal Management

12:30 **Group Photo**

12:45 **Lunch**

1:45 **Case Study 1**
Stranded: Avoiding the perils of unknown environments through the synthesis of energy, soil, and adversary localization maps

Faculty:	Kira Barton, Dimitra Panagou (University of Michigan) Ardalan Vahidi (Clemson University) Lauro Ojeda (University of Michigan)
Student:	Michael Quann (University of Michigan)
Government:	Denise Rizzo, William Smith (U.S. Army TARDEC)
Industry:	Frank Koss, Andrew Dallas (SoarTech)

Abstract

2:30 **Case Study 2**
I Want It All: Achieving High Fidelity and Optimal Computational Complexity in Physics-Based Off-Road Mobility Simulations

Faculty:	Hiroyuki Sugiyama (University of Iowa) Shravan Veerapaneni (University of Michigan) Hiroki Yamashita (University of Iowa)
Post-doc.:	Eduardo Corona (University of Michigan)
Student:	Guanchu Chen (University of Iowa)
Government:	Paramsothy Jayakumar, Yeefeng Ruan (U.S. Army TARDEC) Kenneth Leiter (U.S. Army Research Laboratory)
Industry:	Mustafa Alsaleh (Caterpillar Inc.)

Abstract

3:15 **Break**

3:30 - 5:30 **Poster Session** (PDF of session layout and poster index)
Researchers will give in-depth exposition of their research by their posters. We expect an exciting exchange of ideas.

5:30 - 7:30 **Networking - Strolling Dinner**
Johnson Rooms, Lurie Engineering Center

Day 2 Agenda
Thursday May 17

9:00 **Check-in and Breakfast**

9:30 **Panel**:
How Soon is Now?
Creating the Future of Autonomous High Mobility Ground Systems

Panelists

Dr. Sean Brennan
Professor of Mechanical Engineering, Penn State University

Dr. Chris Gerdes
Professor of Mechanical Engineering, Stanford University

Dr. David Gorsich
Chief Scientist, U.S. Army TARDEC

Dr. Reza Langari
J. R. Thompson Chair and Department Head, Texas A&M University

Ms. Carrie Morton
Deputy Director, Mcity

Dr. Raju Namburu
Chief for Computational Sciences Division, Army Research Laboratory

Moderator
Prof. Bogdan Epureanu
Director, Automotive Research Center

Technological revolutions in autonomy are fueling the third offset strategy in the U.S. military. This is despite the strong uncertainty in future military operations and needs. Building military systems for deterministic predictions of the future is unaffordable because technological development is highly stochastic. At the same time, evolving adversaries make it unaffordable to "wait and see". To address these conflicting trends, the ARC vision is to define the future of military autonomous ground systems rather than trying to predict it. Instead of rushing to build assets to accommodate the world as it is now, we aim to define the future and then build highly adaptable systems to address it. What is almost certain is that future military autonomous ground systems will be highly diverse and adaptive so they can respond to the unknown. The panel will discuss challenges and opportunities in realizing this vision and in creating the future of autonomous ground systems. How soon is now?

11:00 **Break**

11:15 **Technical Session 2** (matrix of parallel sessions)

2A: Structures, Systems & Reliability

2B: Fuels & Powertrains

12:55 **Closing Remarks and Award Presentation**
Dr. Alec Gallimore
Robert J. Vlasic Dean of Engineering, University of Michigan

Dr. David Gorsich
Chief Scientist, U.S. Army TARDEC

Prof. Bogdan Epureanu
Director, Automotive Research Center

Poster Awards Committee

1:15 - 2:30 **Post Review Networking**

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ARC

Biographies

Dr. Chris Gerdes is a Professor of Mechanical Engineering and, by courtesy, of Aeronautics and Astronautics at Stanford University. His laboratory studies how cars move, how humans drive cars and how to design future cars that work cooperatively with the driver or drive themselves. When not teaching on campus, he can often be found at the racetrack with students. Vehicles in the lab include X1, an entirely student-built test vehicle; Shelley, an automated Audi TT-S that can lap a racetrack as quickly as an expert driver; and MARTY, an electrified DeLorean capable of controlled drifts. Chris and his team have been recognized with a number of awards including the Presidential Early Career Award for Scientists and Engineers, the Ralph Teetor award from SAE International and the Rudolf Kalman Award from the American Society of Mechanical Engineers.

From February 2016 to January 2017, Chris served as the first Chief Innovation Officer at the United States Department of Transportation. In this role, he worked with Secretary Anthony Foxx to foster the culture of innovation across the department and find ways to support transportation innovation taking place both inside and outside of government. He was part of the team that developed the Federal Automated Vehicles Policy and represented the Department on the National Science and Technology Committee Subcommittee on Machine Learning and Artificial Intelligence.

Chris is a co-founder of truck platooning company Peloton Technology and served as Peloton's Principal Scientist before joining U.S. DOT.

Dr. David Gorsich was selected for a Scientific and Professional (ST) position in January 2009 and serves as the Army's Chief Scientist for Ground Vehicle Systems. His current research interests are vehicle dynamics and structural analysis, reliability based design optimization, underbody blast modeling, terrain modeling and spatial statistics.

Prior to his current position, Gorsich served as the U.S. Army Tank Automotive Research, Development and Engineering Center's (TARDEC's) Associate Director, Modeling and Simulation (M&S), from July 2003 to December 2008. He has also served as the Acting Director, Strategic Plans and Programs, and the Team Leader for Robotics and Vehicle Intelligence. He served in various assignments at TARDEC, the Army Materiel Command, the Army Research Laboratory and for the Assistant Secretary of the Army (Acquisitions, Logistics and Technology). Gorsich previously was an electrical engineer with McGraw Commercial Equipment Corporation in Novi, MI.

Gorsich was named a Society of Automotive Engineers (SAE) Fellow in 2008. He has served on the SAE Technical Standards Board for a 3-year term, been the chair for the SAE International Standards Committee for Ground Vehicle Reliability and also on the SAE Board of Directors. He has received several Commander's Coins, including: U.S. Army Central Command, GEN John Abizad, High Mobility Multipurpose Wheeled Vehicles Safety/Seat Experiments, 2005; Chief of Staff, GEN Peter Schoomaker, TARDEC M&S, 2005; West Virginia National Guard, 2004; U.S. Army TACOM, MG William M. Lenaers, Army-SAE Partnership, 2004; U.S. Army TACOM, MG N. Ross Thompson, Reliability, 2003. Gorsich received the Detroit Federal Executive Board Award in 2001. Gorsich was recognized with the 1997 Army Research, Development and Acquisition Award, "Innovations in Ground Vehicle Signature Research."

Gorsich is recognized in many professional organizations for his research accomplishments. Gorsich serves as an Associate Editor for the International Journal of Terramechanics, and on the Editorial Board of the International Journal for Reliability and Safety, and as past Associate Editor for the Journal of Mechanical Design. He is a member of the Massachusetts Institute of Technology (MIT) Chapter of Sigma Xi, the Material Parts and Processes Council of SAE and the Senior Executives Association, ST Chapter.

Gorsich has published more than 150 conference and journal articles including more than 50 peer reviewed journal articles. He has published in the following peer reviewed journals: Transactions of SAE; International Journal of Vehicle Design; Journal of Mechanical Design; Journal of Commercial Vehicles; Contemporary Mathematics; Computational Statistics and Data Analysis; Physical Review D; Society of Automotive Engineers; Journal of Multivariate Analysis; Journal of Electronic Imaging; Optical Engineering; Pattern Recognition Letters; Statistics and Computing; Institute for Electrical and Electronics Engineers Transactions on Pattern Analysis and Machine Intelligence.

Gorsich holds a B.S. in electrical engineering from Lawrence Technological University. He holds an M.S. in applied mathematics from George Washington University and a Ph.D. in applied mathematics from MIT.

Dr. Sean Brennan is a Professor of Mechanical Engineering at Penn State University where he has taught since 2003. He leads the Intelligent Vehicles and Systems Group, consisting of roughly 20 to 30 engineers in research focused on vehicle dynamics and automation both at high speeds such as highway vehicles and high-speed off-road maneuvering, and low speeds such as bomb-disposal robotics, automated wheelchair systems, and nuclear inspection robotics. His diverse research applications are unified by a focus on model-based control and estimation algorithms that utilize location-specific information compression – i.e. using maps with feedback control algorithms. Prof. Brennan currently leads Penn State's vehicle activity at the Larson Transportation Institute test track, one of the ten USDOT-designated Autonomous Vehicle Proving Grounds. His research has resulted in approximately 150 peer-reviewed publications to date.

In 2008, he was awarded the SAE Teetor Award. He also won PSU's Premier Teaching Award in 2011, PSU's Outstanding Teaching Award in 2008, and the 2005 PSU Quality Improvement Award. He has served as an Associate Editor of the Journal of Dynamic Systems, Measurement as well as the IEEE Transactions on Control Systems Technology, and he has been the past chair, vice-chair, secretary, and conference organizer for ASME's Dynamic Systems and Control Technical Committee on Automotive and Transportation Systems.

Dr. Reza Langari (SM'02) received the B.Sc., M.Sc., and Ph.D. degrees from University of California, Berkeley, CA, USA, in 1981, 1983, and 1991, respectively. He was with Measurex Corporation; Integrated Systems, Inc.; and Insight Development Corporation prior to starting his academic career with Texas A&M University, College Station, TX, USA, in September 1991. He has since held research positions at the NASA Ames Research Center, the Rockwell International Science Center, the United Technologies Research Center, and the U.S. Air Force Research Laboratory. His expertise is in the area of computational intelligence, with application to mechatronic systems, robotics and automation, and automated vehicles. He has co-authored Fuzzy Logic: Intelligence, Control and Information (Prentice Hall, 1999) and Measurement and Instrumentation [Elsevier, 2011, 2015 (2nd edition)] and has coedited Fuzzy Control: Synthesis and Analysis (Wiley, 2000) and Industrial Applications of Fuzzy Systems (IEEE Press, 1995). Dr. Langari has served as an Associate Editor of IEEE Transactions on Fuzzy Systems, the IEEE Transactions on Vehicular Technologies, and ASME Journal of Dynamic Systems, Measurement, and Control. He currently serves as the Editor-in-Chief of Journal of Intelligent and Fuzzy Systems.

Ms. Carrie Morton oversees day-to-day operations of Mcity, the University of Michigan's public-private partnership devoted to advancing the development of connected and automated vehicles. She is actively involved in supporting strategy development and execution, and fosters collaboration among Mcity's industry, government and academic partners.

Prior to joining Mcity, Morton served a dual role at the University of Michigan Energy Institute. As director of business development, she helped broaden industrial relationships with energy faculty. Morton also served as assistant director for collaboration and industry outreach for the US-China Clean Energy Research Center – CleanVehicle Consortium.

Morton joined the university in 2011 after more than a decade in the automotive industry, primarily with the Robert Bosch Corporation. In her last role at Bosch, she was manager of government projects and responsible for leading all publicly funded research projects, with a focus on engine combustion.

Morton holds a Bachelor of Science degree in Mechanical Engineering and a Master of Engineering degree in Automotive Engineering, both from the University of Michigan.

Dr. Raju Namburu is the Chief for Computational Sciences Division at ARL. Dr. Raju Namburu received his Ph.D. in Mechanical Engineering from the University of Minnesota. Dr. Raju Namburu's research and development activities include computational sciences, computational mechanics, interdisciplinary thermal-structural-fluid applications, computational electro-magnetics, network modeling, multi-scale computational methods, and high performance computing. Dr. Namburu has more than 100 publications in various journals and refereed papers in international conferences and symposiums in the areas of computational sciences, computational mechanics, scalable algorithms, network modeling and high performance computing. His awards include the Department of the Army Superior Civil Service Award; Army Research Development and Achievement award 1997, 2001, 2009; and the Army Science best paper awards at the 1998, 2000, and 2002 Army Science Conference. Dr. Namburu is a Fellow of ASME, and a member of USACM, and IACM.

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Case Study Abstracts

Case Study 1

Stranded: Avoiding the perils of unknown environments through the synthesis of energy, soil, and adversary localization maps

Contributors:

Faculty: Kira Barton, Dimitra Panagou (University of Michigan)
Ardalan Vahidi (Clemson University)
Lauro Ojeda (University of Michigan)

Student: Michael Quann (University of Michigan)

Government: Denise Rizzo, William Smith (U.S. Army TARDEC)

Industry: Frank Koss, Andrew Dallas (SoarTech)

This case study brings together three ARC projects to investigate how enhanced situational awareness will improve 3D energy mapping in off-road environments. An important aspect in off-road energy mapping is the synthesis of *a priori* topography information combined with real-time dynamic updates. To address this need, this case study combines an energy-mapping framework with (1) the utilization of static soil and elevation maps to provide a priori information that will enable prioritization of initial areas of interest within the environment based on uncertainties associated with the energy costs of a given location; and (2) dynamic updates from aerial maps that will provide near real-time information about the terrain (wet, dry) and identify "go / no-go" locations in the environment based on adversarial elements. Thus, the soil, terrain, and aerial maps are integrated into the energy-mapping framework for enhanced decision-making. The addition of these maps is expected to improve the reachability analysis and energy mapping efficiency of multi-robot reconnaissance in an unknown environment through the identification of go / no-go locations and targeted areas of interest. A simulation study is used to evaluate the effectiveness of the combined mapping approach.

Case Study 2

I Want It All: Achieving High Fidelity and Optimal Computational Complexity in Physics-Based Off-Road Mobility Simulations

Contributors:

Faculty: Hiroyuki Sugiyama (University of Iowa)
Shravan Veerapaneni (University of Michigan)
Hiroki Yamashita (University of Iowa)

Post-doc.: Eduardo Corona (University of Michigan)

Student: Guanchu Chen (University of Iowa)

Government: Paramsothy Jayakumar, Yeefeng Ruan (U.S. Army TARDEC)
Kenneth Leiter (U.S. Army Research Laboratory)

Industry: Mustafa Alsaleh (Caterpillar Inc.)

A high-fidelity computational vehicle-terrain interaction model is essential for physics-based off-road mobility simulations in achieving accurate mobility performance prediction as well as reliable operational planning. This case study brings together two projects to address accuracy and computational efficiency of physics-based vehicle-terrain interaction simulation capabilities, which can be fully integrated into general multibody dynamics (MBD) simulation algorithms. For this purpose, a hierarchical multiscale terrain dynamics model is developed to eliminate phenomenological assumptions in existing constitutive models and is further extended to tire-soil interaction simulation. The finite-element (FE) model is utilized to predict macroscale soil deformation, while the microscale constitutive behavior is modeled by the representative volume element (RVE) using the discrete-element (DE) approach to describe complex soil failure phenomenon including strain localization. Validation and comparison with single-scale FE and DE approaches are presented. Furthermore, to improve computational efficiency of different components of the coupled MBD-FE-DE vehicle-terrain interaction simulation capability, fast solvers based on hierarchical low-rank factorizations are applied and the ensuing speedups are demonstrated on several test cases.

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Technical Session Matrix

'A' session venue is Boeing Auditorium. 'B' session venue is 1012 FXB.

May 16	**1A: Algorithms & Intelligence** *Session Leads:* *Dr. Paramsothy Jayakumar & Mr. Victor Paul*	**1B: Electrification & Thermal Management** *Session Lead: Dr. Matt Castanier*
10:50	PI: Dr. Jeff Stein Real-time Trajectory Optimization for UGVs	PI: Dr. Heath Hofmann Computationally-Efficient Heat Convection Model for Electric Machines
11:10	PI: Dr. Tulga Ersal Latency Compensation and Human Performance in Teleoperated Unmanned Ground Vehicles	PI: Dr. John Wagner A Hybrid Thermal Bus Cooling System for Military Ground Vehicles and Electric Motors
11:30	PI: Dr. Yue Wang Trust-based Control and Scheduling for Human-UGV Teams	PI: Dr. Simona Onori Tools for Optimal Selection of Energy Storage Technology for Electrified Military Vehicles
11:50	PI: Dr. Brent Gillespie Haptic Shared Control for Remote Steering of an Unmanned Ground Vehicle	PI: Drs. Anna Stefanopoulou, Jason Siegel Advanced Battery Diagnostics Based on Electrode Particle Strain and Cell Swelling
12:10 - 12:30	PI: Drs. Dawn Tilbury & Lionel Robert Modeling bi-directional trust in semi-autonomy for improved system performance	PI: Dr. Jason Siegel AVPTA Optimization of Scalable Military Fuel Cell Hybrid Vehicles

May 17	**2A: Structures, Systems & Reliability** *Session Lead: Dr. Ravi Thyagarajan*	**2B: Fuels & Powertrains** *Session Lead: Dr. Pete Schihl*
11:15	PI: Drs. Zissimos Mourelatos & Vijit Pandey Reliability Assessment and Warranty Forecasting of Repairable Systems using a New Limited Failure Population Approach	PI: Dr. Angela Violi Combustion Chemistry of Jet Fuels: From Atomistic Simulations to Mechanism Development
11:35	PI: Dr. Bogdan Epureanu Intelligent Operation System for Autonomous Military Vehicle Fleets	PI: Dr. André Boehman Bulk Modulus of Compressibility Measurements of Conventional and Alternative Military Fuels
11:55	PI: Dr. Georges Fadel Design and Bi-level Optimization of a Multiple Metamaterial Tank Track Pad and Road Wheel System	PI: Dr. André Boehman Ignition Studies for Kinetic Mechanism Development and Validation
12:15	PI: Drs. Bogdan Epureanu & Heath Hofmann Multi-physics Reduced-Order Models of Electro-Magnetic Structural (EMS) Dynamics	PI: Dr. Marcis Jansons Boundary Conditions for Predictive Combustion Simulation
12:35 - 12:55	PI: Dr. Nick Vlahopoulos Modeling Shear Thickening Fluids in Multilayered Plates under Blast Loading	PI: Dr. Marcis Jansons Thermal Barrier Coatings for Reduction of Cooling Loads in Military Vehicles

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Technical Symposia Abstracts

Technical Session 1A – Algorithms & Intelligence

1A1: Real-time Trajectory Optimization for UGVs

Quad members: Tulga Ersal (PI), Jeffrey L. Stein (Co-PI), Huckleberry Febbo (University of Michigan); Paramsothy Jayakumar, Mark J. Brudnak (U.S. Army TARDEC); Mitchell Rohde, Steve Rohde, (Quantum Signal LLC)

The motion planning system for a large unmanned ground-vehicle (UGV) moving at high-speeds is well posed as an optimal control problem (OCP), but difficult to solve in real-time. In previous work, an OCP was designed that considered both the vehicle's dynamical limits and moving obstacles. To overcome inherent difficulties of solving this type of OCP in real-time (2 Hz), we developed a fast OCP software package called NLOptControl.

In this work we evaluate NLOptControl's ability to solve the aforementioned OCP in real-time. To accomplish this, a variety of solver configurations are tested for various environments. Where, the environment is characterized by a set of moving obstacles. The solver configurations tested are: direct transcription methods, NLP solvers, constraint violation tolerances, and the number of collocation points. The results will be discussed.

In addition, we will discuss our plan to move towards experimental testing in unknown environments. More specifically, our robot operating system (ROS)-based UGV proving ground will be introduced. Wherein, NLOptControl, a high-fidelity Chrono HMMWV model, and a 3D LiDAR model in Gazebo are all incorporated.

1A2: Latency Compensation and Human Performance in Teleoperated Unmanned Ground Vehicles

Quad members: Tulga Ersal (PI), Jeffrey L. Stein, Xi Jessie Yang, Yingshi Zheng, Yue Tang, Shihan Lu, Meng Yuan Zhang (University of Michigan); Mark Brudnak, Paramsothy Jayakumar (U.S. Army TARDEC); Mitch Rohde, Steve Rohde (Quantum Signal); James Poplawski (Zenuity); Hossein Mirinejad (FDA)

This project is motivated by the Army's need to increase the performance of teleoperated unmanned ground vehicles in terms of mobility and drivability. One difficulty with teleoperation is that communication delays can significantly affect the teleoperation performance and make teleoperated driving tasks very challenging, especially at high speeds. The first part of this talk will summarize our efforts in a recently completed ARC project to compensate the delays to improve teleoperation performance, including the theoretical developments and driver-in-the-loop simulation results. The results will highlight the impact of the delay compensation not only on teleoperation performance, but also on driver cognitive workload. The second part of the talk will highlight our ongoing efforts to mathematically capture the performance of human teleoperators across different delays and speeds by leveraging a cognitive architecture. Results will show that this framework has the potential to predict the best performance that can be expected from human teleoperators well, thereby serving as an important first step towards enabling fully simulation-based and thus accelerated evaluation of unmanned ground vehicle technologies.

1A3: Trust-based Control and Scheduling for Human-UGV Teams

Quad members: Yue Wang (PI), John Wagner (Co-PI), Fangjian Li, Chengshi Wang, Jessica Manning (Clemson University); Dariusz Mikulski (U.S. Army TARDEC); Andy Dallas (SoarTech)

Unmanned ground vehicles (UGVs) may not be capable of handling abnormal situations while human intelligence can be utilized. However, when a human operator supervises multiple UGVs, their performance degrades due to cognition limits. Therefore, it is necessary to design an automated decision-making aid to effectively team a human operator with multiple UGVs for optimal performance. Here we consider the UGV convey platoon which might suffer from hardware and/or software failures. The automated decision-making aid consists of three parts. The first part is trust-based information management system (TIMS). The RoboTrust algorithm is utilized to evaluate vehicle trustworthiness and rule out information with low credit. Based on the information, TIMS determines the UGVs that need human assistance. The second part is the switched control of UGVs. In normal situations, the UGVs operate under the default autonomous mode. When abnormal situations (e.g. cyber attacks) occur, on-board resilient control can be used to mitigate the negative effects but the manual teleoperation of UGVs is still preferred. The third part considers the scheduling problem of human-robot teaming. The states of UGVs under the resilient control will be predicted for future steps and the UGV with worst predicted behavior will be assigned with human assistance.

1A4: Haptic Shared Control for Remote Steering of an Unmanned Ground Vehicle

Quad members: Brent Gillespie (PI), Lars Watts, (University of Michigan); Amirhossein Ghasemi (UNC Charlotte); Paramsothy Jayakumar (U.S.Army TARDEC); John Walsh (Ford Motor Company)

Safety is often compromised when control is transitioned between a human and automation system. Haptic Shared Control has been proposed as a means to realize smooth control transitions by defining periods during which the human and automation system share control, with hand and motor simultaneously acting on the steering wheel. The human becomes aware of the automation's action by virtue of haptic feedback in the axis of control. We examined the performance of 24 participants at avoiding obstacles in a driving simulator while sharing control with and without haptic feedback and with either discrete (mediated through a button-press) or continuous (always sharing) transitions of control. In half of the trials, participants performed a secondary externally paced visual task. Results indicate that continuous transitions carry an advantage for secondary task performance and haptic communication aides in avoiding obstacles.

1A5: Modeling bi-directional trust in semi-autonomy for improved system performance
Quad members: Dawn Tilbury (PI), Lionel Robert Xi Jessie Yang, Luke Petersen, Huajing Zhao (University of Michigan); Victor Paul, Ben Haynes (U.S. Army TARDEC); Mitch Rohde (Quantum Signal, LLC)

Autonomous and semi-autonomous vehicles have the potential to help drivers successfully and safely complete many military missions while providing the drivers with the flexibility to address other pressing issues. Unfortunately, drivers have failed to fully leverage a vehicle's autonomy because of a lack of trust in the vehicle's autonomy. This project examines the factors that impact a driver's trust in the vehicle's autonomy and vice versa. The goal is to develop methods to predict (1) when the human is likely to take or give control of the driving to the vehicle's autonomy, and (2) when the vehicle's autonomy should take or give control of the driving to the driver. In this talk, we will review the results of two human-in-the-loop experiments that have been conducted to date and discuss the modelling framework that has been developed around the data collected in these studies..

<u>Technical Session 1B – Electrification & Thermal Management</u>

1B1: Computationally-Efficient Heat Convection Model for Electric Machines
Quad members: Heath Hofmann (PI), Yuanying Wang (University of Michigan); Denise Rizzo, Scott Shurin (U.S. Army TARDEC); John Wagner, Richard Miller (Clemson University); Jon Zeman (Gamma Techonologies); Arun Muley (Boeing)

The performance of electric machines is greatly influenced by thermal behavior, therefore knowledge of the temperature profile inside electric machines is very important information for assessment of torque and power capabilities, condition monitoring, and protection. In previous work, an FEA-based computationally-efficient heat conduction model for electric machines was proposed. In this project, a computationally-efficient model of heat convection in the air region of the machine is proposed which is capable of quickly calculating the heat flux at the boundaries of the rotor and stator as a function of the rotor and stator temperatures and rotor speed. The presented work considers the rotor speed ranges dominated by i) laminar flow and ii) Taylor vortices. The accuracy of this new model is compared to CFD simulation results, where an error of less than 0.3 % is shown over the studied operating range. Initial experimental results will be provided as well.

1B2: A Hybrid Thermal Bus Cooling System for Military Ground Vehicles and Electric Motors
Quad members: John Wagner, Richard Miller, Shervin Shoai-Naini, Junkui (Allen) Huang (Clemson University); Heath Hofmann (University of Michigan); Denise Rizzo, Katie Sebeck, Scott Shurin (U.S. Army TARDEC); Arun Muley, David Blanding (Boeing Research & Technology)

The management of thermal loads in military ground vehicles remains a challenge due to powertrain configurations and adverse operating conditions. Traditional cooling systems rely on ethylene glycol that circulates throughout the propulsion system to reject heat to the ambient using radiators with fans. However, alternative passive and active cooling strategies can be implemented to facilitate "silent sentry" and other operating modes. This study investigates the integration of highly effective thermal conductivity passive "thermal bus" pathways for improved efficiency and reduced weight/size. In the first case, a hybrid approach featuring loop heat pipes, carbon fibers, and advanced high thermal conductivity materials works with the conventional cooling system. This hybrid cooling system is based around a novel thermal bus structure used to passively route heat from the source to a heat exchanger and then to the ambient. Next, a compact e-motor housing structure, referred to as a "cradle", is designed with multiple heat pipes to route the thermal load to the bus. Representative simulation results over various driving profiles demonstrate that the cooling system operating time can be significantly reduced for moderate heat rejection scenarios while maintaining the heat load operating temperatures within their prescribed ranges.

1B3: Tools for Optimal Selection of Energy Storage Technology for Electrified Military Vehicles
Quad members: Zoran Filipi, Simona Onori, Abdullah-al Mamun, Zifan Li (Clemson University); Aric Haynes, Denis Rizzo (U.S. Army TARDEC); Vincent O Dominguez (Boeing Research and Technology)

The objective of this research is to develop a set of modeling and optimization tools for optimal design, selection and utilization of energy storage technologies towards the electrification of the wide range of military vehicles. A scalable design framework for vehicle hybridization, in terms of either single or multiple energy storage technologies, and their optimal usage is pursued in this research to extract maximum fuel savings out of the wide spectrum of military vehicles ranging from 50 lbs to 50 tons weight.

With this goal in mind, the optimal energy storage design and optimal power split among different powertrain components are combined into a unified optimization framework by coupling a global, heuristic optimization algorithm with an optimal control technique developed using Pontryagin's minimum principle (PMP) from calculus of variations. Energy storage systems (in their standalone or hybrid configuration) are optimally evaluated to understand their ability to handle high power demand and their relative benefit in terms of fuel consumption.

1B4: Advanced Battery Diagnostics Based on Electrode Particle Strain and Cell Swelling
Quad members: Anna Stefanopoulou (PI), Jason Siegel (PI), Peyman Mohtat (University of Michigan); Yi Ding, Matt Castanier (U.S. Army TARDEC); Aaron Knobloch (GE Global Research)

One of the important aspects of a State of Health (SOH) estimation algorithm is to not only give a measure of the cell capacity but also to provide information on the degradation mechanism of individual electrodes so that the battery management system stretches the operational limits but avoids further degradation. In this project, it is shown that under practical limitations in the availability of data, stress or strain measurements using externally attached sensors provide the needed identifiability of the individual electrode parameters. Our method uses the intrinsic phase transitions of the intercalation material used in Li-ion batteries. It is shown that having a physics-based model of the particle-electrode electromechanical response of its fundamental phase transitions is recognizing important degradation phenomena such as loss of active material (LAM) in the anode or cathode based on cell measured voltage and stress.

1B5: AVPTA Optimization of Scalable Military Fuel Cell Hybrid Vehicles
Quad members: Jason Siegel, Niket Prakash (University of Michigan); Youngki Kim, Hadi Abbas (University of Michigan Dearborn); Denise Rizzo, David Alyass (U.S. Army TARDEC); Buz McCain (Ballard Power Systems Inc.)

This research develops scalable physics-based modeling and simulation tools to address right sizing and power split control for Proton Exchange Membrane (PEM) Fuel Cells (FC) hybridized with a lithium ion battery pack to meet the high power demand requirements of military drive cycles and extreme environmental conditions in temperature and humidity. The models need to scale for vehicle powertrains ranging from 300W robots to 250kW vehicles to a 750kW armored tank.

When hybridizing a power train, it is challenging to size the energy buffer (EB) or lithium ion battery and range extender (PEMFC) because the drive cycle, the control policy, and the hardware architecture all affect the optimal size and cooling requirements. The PEMFC system models include dynamics and parasitic losses associated with balance of plant components such as hydrogen storage, compressor, pumps, fans and radiators, that capture the relevant tradeoffs in designing hybrid systems. The key performance metrics include power output, fuel consumption, startup time, volume and weight. The developed control strategies are compared with the baseline optimal solution found using Dynamic Programming.

Technical Session 2A – Structures, Systems & Reliability

2A1: Reliability Assessment and Warranty Forecasting of Repairable Systems using a New Limited Failure Population Approach
Quad members: Themistoklis Koutsellis (GSRA), Zissimos P. Mourelatos (PI), Vijitashwa Pandey (co-PI) (Oakland University); Matt Castanier, Monica Majcher (U.S. Army TARDEC); Mohammad Hijawi (Fiat Chrysler Automobiles)

Most engineering systems are repairable. Their components can be renewed or repaired after a system failure, to put the system back into service. We use a Generalized Renewal Process (GRP) model to quantify the reliability of a repairable system based on the concept of virtual or effective age. The model accounts for repair assumptions such as "same-as-old," "good-as-new," "better-than-old-but-worse-than-new" and "worse-than-old," and is suitable for reset and depot maintenance strategies as well as warranty prediction and forecasting of vehicle fleets. In warranty forecasting, it is desired to predict the Expected Number of Failures (ENF) after a censoring time using collected failure data before the censoring time. We will present a new analytical forecasting method to predict the ENF of a repairable system using observed data. The method considers the existence of a small subpopulation with a high failure rate, called Limited Failure Population (LFP), which dominates early observed failures. The approach is analytical and can predict the ENF of a repairable system very accurately even with a small number of observed failures. A GRP model is first developed using the observed data and then the model is used to forecast failures. All developments will be demonstrated using simple examples and vehicle production data.

2A2: Intelligent Operation System for Autonomous Military Vehicle Fleets
Quad members: Xingyu Li, Bogdan Epureanu (PI), Panos Papalambros (Co-PI) (University of Michigan); Matthew Castanier, Richard Gerth (U.S. Army TARDEC); Ra'ed Seifeldin (ONR); Edward Umpfenbach (General Motors)

This presentation focuses on the autonomous teaming of modular assets. Modularity has long been viewed as a way to control acquisition and sustainment costs while increasing capability and adaptability of fielded systems. Inclusion of autonomy in the modular fleet operation has the potential to extend the capabilities of these systems, i.e., long-range strike and information acquisition. However, removing the human operator changes the decision-making capabilities and leads to a new dynamic fleet behavior in military operation, in which communication is restricted. To capture the synergies between modularity and autonomy, the strategies for knowledge sharing and negotiation among vehicles are required for improving the overall fleet performance. Real-time negotiations promote the formation of teams and exchange of their resources, to enable autonomous vehicles to achieve their goals collaboratively and effectively. In this study, decision-making tasks are allocated to various intelligent agents, which are capable to store and analyze the enemy's known actions in order to forecast their behavior. Based on this information, agents can achieve also information sharing according to algorithms, and they can schedule on-field actions to achieve their goals as a team. We formulate attacker-defender games between two intelligent forces (modular fleet and conventional fleet) in different mission scenarios, to emphasize the advanced tactics and superior performance brought from the synergistic combination of autonomy and modularity.

2A3: Design and Bi-level Optimization of a Multiple Metamaterial Tank Track Pad and Road Wheel System
Quad members: Samuel J. Franklin, Georges Fadel (PI), Gang Li, Nicole Coutris (Clemson University); William Vanslembrouck, Michael Honaker (General Dynamics Land Systems)

This talk continues the implementation and refinement of the Modified Unit Cell Synthesis method, used to design cellular meta-materials for targeted nonlinear deformation. By using models to benchmark the behavior of the wheel/pad track system of an M1 tank, the favorable mechanical responses that need to be replicated by the new material were gathered. The results led to the implementation of a circular meta-material for use on the road wheel, similar to a previously designed backer pad, and a model was created to check the feasibility of successful multi-objective optimization. A separate model was created to represent the interaction of the original and new meta-materials, for use in a bi-level optimization. The optimization method should provide two meta-material bodies that behave in close accordance with their rubber counterparts, while also mimicking the global response of the entire rubber-rubber system. A comparative assessment will also be conducted, using a single level optimization technique, to compare the final designs obtained and the deformation responses of both the individual parts and whole system. Lastly, a sensitivity analysis of the final design parameters will be conducted, proactively predicting the range of response that can be expected from manufactured parts, with respect to production tolerances.

2A4: Multi-physics Reduced-Order Models of Electro-Magnetic Structural (EMS) Dynamics
Quad members: Bogdan I. Epureanu (PI), Heath Hofmann (Co-PI), Mohammad Khodabakhsh, Chenyu Yi, (University of Michigan); Matthew Castanier, Denise Rizzo (U.S. Army TARDEC); Xiao Guang Yang (Ford); Dean Tomazic, Kiran Govindswamy (FEV)

The increasing demand for silent move, silent watch, and higher energy efficiency of ground systems requires the design and optimization of hybrid electric architectures to reduce noise while enhancing the performance of electro-magnetic-structural systems used in hybrid powertrains. Design and optimization of hybrid powertrain architectures requires accurate yet computationally efficient models for both vehicle driving simulations and structural analysis. In addition to the vibratory electromagnetic forces created in electric machines, other excitations are significant also in most hybrid electric powertrains (e.g., torque fluctuations). Both the electromagnetic forces and the torque fluctuations can cause vibrations in the electric machine. In turn, these vibrations affect the electromagnetic forces, leading to a fully coupled electro-magnetic-mechanical (EMM) coupling. In this project, first a unique hybrid electric powertrain architecture was designed, modeled, and optimized. Next, the attention was devoted to constructing reduced-order models which capture the EMM coupling in the electric machines that compose the powertrain. A co-energy based technique was created to calculate electromagnetic forces in the modal space, and those forces were integrated with the structural reduced-order models. The presentation discusses the overall architecture of the powertrain, followed by results for the electromagnetic force calculation and the structural models with EMM coupling.

2A5: Modeling Shear Thickening Fluids in Multilayered Plates under Blast Loading
Quad members: Alyssa Bennett, Nickolas Vlahopoulos (PI) (University of Michigan); Weiran Jiang (Ford Motor Company); Matt Castanier, Ravi Thyagarajan, Scott Shurin (U.S. Army TARDEC)

Multilayered plates are a field of interest for improving blast survivability and reducing structural weight due to the variety of possible material and structural configurations they provide. A proposed new structural configuration in multilayered plates is to implement shear thickening fluids between plate layers to act as a shock absorbing mechanism, which may allow for lighter material configurations. To study the shear thickening mechanisms, a model was developed in STAR-CCM+. The results from this model were then implemented into a reduced order model of a multilayer plate subjected to blast loading conditions. The reduced order model was developed using the reverberation matrix method (RMM), where the effects of the shear thickening fluid were implemented in the shear stresses at the layer interfaces. The results of this reduced order model are used to study the effects of shear thickening fluids on the structural response of multilayered plates..

Technical Session 2B – Fuels & Powertrains

2B1: Combustion Chemistry of Jet Fuels: From Atomistic Simulations to Mechanism Development
Quad members: Paolo Elvati, Doohyun Kim, Angela Violi (University of Michigan)

In recent years, there has been an increasing effort to incorporate complex reaction mechanisms in simulations of reacting flows, such as the combustion process in engines. One of the key components is the accurate description of the kinetic network of reactions that develop during combustion. Identifying the main pathways as well as missing pathways in the current kinetic mechanisms is required for the construction of chemical mechanisms more accurate than the current ones. Such knowledge of combustion chemistry is also critical for reduction of detailed chemical mechanisms, which is necessary for multidimensional reactive flow simulations. In this talk, we present our latest results on the study of important reaction pathways using a combination of computational methods as well as a new network analysis for reducing the complexity of mechanisms.

2B2: Bulk Modulus of Compressibility Measurements of Conventional and Alternative Military Fuels
Quad members: Taemin Kim, Andre Boehman (PI) (University of Michigan); Eric Sattler (U.S. Army TARDEC); James Anderson (Ford Motor Company)

This project concerns the bulk modulus of conventional and alternative jet fuels, and jet fuel surrogates and investigation of the impact of bulk modulus of fuel on fuel injection timing in pump-line-nozzle type fuel supply systems. The isothermal bulk modulus of compressibility of conventional and alternative fuels was measured using a unique apparatus, and comparisons to the isentropic bulk modulus were performed. A single cylinder, direct-inject, pump-line-nozzle type fuel supply engine was configured for the purpose of the investigation of the different injection timing shifts with these alternative and conventional jet fuels. An outcome of the project is a correlation of the relationship between the isothermal bulk modulus and the injection timing shift, which can help guide the calibration and design of fuel injection systems.

2B3: Ignition Studies for Kinetic Mechanism Development and Validation
Quad members: Shuqi Cheng, André Boehman (PI), Margaret Wooldridge, Marcis Jansons, Angela Violi (University of Michigan); Peter Schihl (U.S. Army TARDEC); James Anderson (Ford Motor Company); J. Timothy Edwards (U.S. AFRL)

The research objectives are to generate ignition data for the purpose of quantifying fuel reactivity and providing high fidelity data for developing reaction theory and reaction mechanisms, and for developing and validating reduced kinetic mechanisms for use in engine simulations. To achieve these objectives, an experimental approach will be used with combines the strengths of two existing experimental systems. The first is a modified CFR Octane Rating Engine (used in a previous ARC 4.17 project) with added instrumentation to generate the data needed for the validation of kinetic mechanisms and optimization of the reduced mechanisms. The second is The University of Michigan rapid compression facility which is a unique system that will be used to generate ignition and reaction pathway data at kinetically limited conditions relevant to engine conditions.

2B4: Boundary Conditions for Predictive Combustion Simulation
Quad members: Saarang Sharma, Marcis Jansons (PI) (Wayne State University); Peter Schihl (U.S. Army TARDEC); Bruce Geist (Fiat Chrysler Automobiles)

A challenge to predictive compression-ignited IC engine simulations is lack of knowledge of thermal boundary conditions. Engine thermal conditions strongly affect most global combustion parameters including ignition delay, combustion phasing, cycle work, and heat loss. Fuel temperature at the time of injection is known to affect fuel evaporation rates, liquid length, and fuel vapor distribution, thus influencing wall fuel wetting, cold starting and engine performance, particularly during transients. However, these effects of fuel temperature on alternative jet fuel sprays remains largely unknown. This project examines the effects of injector tip temperature on fuel liquid length penetration and fuel vapor distribution for several types of jet fuels used by the military in reciprocating piston engines. Experiments are conducted in an optical engine under temperature and pressure conditions representative of conditions encountered in military engines. Measurements obtained are also used to provide boundary condition values and validation data for the predictive modeling and surrogate development efforts of ARC partners.

2B5: Thermal Barrier Coatings for Reduction of Cooling Loads in Military Vehicles
Quad members: David Gatti, Marcis Jansons (PI) (Wayne State University); Eric Gingrich (U.S. Army TARDEC); Shawn Dolan (Henkel of America, Inc.)

Reductions in cooling loads are sought to reduce the considerable under-armor volume devoted to thermal management systems comprising ballistic grilles, fans, ductwork and radiators. The project examines the viability of thermal barrier coatings (TBC) as a means of re-distributing cooling load to engine exhaust. Titanium-based coatings applied with a novel aqueous electro-deposition process show promise in overcoming the durability issues characteristic of previously researched materials. A conjugate heat transfer model is developed to examine the effects of TBC properties including thickness, thermal conductivity, diffusivity and inertia on cooling load and efficiency. Effects of optimal properties are further examined in 3-D CFD simulations. Experimentally, thermal fatigue tests are conducted on titanium dioxide and zirconia coated samples to evaluate their durability. Optical diagnostics are applied to observe in-cylinder temperature boundary layers over uncoated and TiO_2-coated pistons during the compression stroke.