Automotive Research Center
A U.S. Army RDECOM Center of Excellence for Modeling and Simulation of Ground Vehicles led by the University of Michigan

10TH ANNUAL ARC CONFERENCE
CONFERENCE OBJECTIVES
Registration closed May 10th, 2004
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10th Annual ARC Conference
May 18–19, 2004

Held at the
Four Points by Sheraton Ann Arbor
3200 Boardwalk, Ann Arbor, Michigan 48108-1799

For inquiries, please email Janet Lyons
jmlyons@umich.edu

Organized by the
Automotive Research Center

Sponsored by
U.S. Army Research, Development and Engineering Command (RDECOM)
U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
National Automotive Center (NAC)

Automotive Research Center
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1231 Beal Avenue
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Day 1, Tuesday, May 18, 2004 Schedule

7:30 - 8:30 am	**ARRIVAL AND CONTINENTAL BREAKFAST**
8:30 - 9:00	**WELCOME AND INTRODUCTIONS** **Dennis Assanis** Professor and ARC Director, The University of Michigan **Walter Bryzik** Chief Scientist, U.S. Army RDECOM-TARDEC **Richard E. McClelland** Director & President, U.S. Army RDECOM-TARDEC **Stephen W. Director** Robert J. Vlasic Dean of Engineering, The University of Michigan
9:00 - 10:30	**TOWARDS FUTURE VEHICLE CONCEPTS AND DESIGNS - EFFICIENT AND RELIABLE VEHICLE SOLUTIONS FOR AN UNCERTAIN WORLD** Moderator: **Dennis Assanis** Professor and ARC Director, The University of Michigan Speakers: **General Paul J. Kern** Commanding General, U.S. Army Materiel Command **Gerhard Schmidt** Vice President Research & Advanced Engineering, Ford Motor Company **Larry Burns** Vice President, Research & Development and Planning, General Motors **Question and Answer Session**
10:30 - 11:00	**NETWORKING BREAK**
11:00 - 11:30	**DEVELOPING MODELING AND SIMULATION TOOLS** Speaker: **David Gorsich** Associate Director, Modeling and Simulation, US-Army RDECOM-TARDEC
11:30 - 11:45	**AUTOMOTIVE RESEARCH CENTER: PAST, PRESENT AND FUTURE** Speaker: **Dennis Assanis** Professor and ARC Director, The University of Michigan
11:45 - 1:00 pm	**LUNCH**

1:00 - 1:45	**CLEAN AND CONTROLLABLE, ADVANCED COMPRESSION IGNITION ENGINE SYSTEM FOR IMPROVED POWER DENSITY AND FUEL ECONOMY**	
	Speakers:	**Dennis Assanis** Professor and ARC Director, The University of Michigan **Zoran Filipi** Associate Research Scientist and ARC Assistant Director, The University of Michigan
1:45 - 2:00	**NETWORKING BREAK**	
2:00 - 2:45	**DESIGN AND ASSESSMENT OF ADVANCED AND ALTERNATIVE TECHNOLOGIES FOR THE FMTV UNDER UNCERTAINTY**	
	Speakers:	**Michael Kokkolaras** Research Scientist, The University of Michigan **Zissimos P. Mourelatos** Associate Professor, Oakland University
2:45 - 3:00	**NETWORKING BREAK**	
3:00 - 3:45	**PREDICTION OF VEHICLE NVH, ACOUSTIC DETECTION AND RELIABILITY OVER THE ENTIRE FREQUENCY RANGE**	
	Speakers:	**Christophe Pierre** Professor and ARC Thrust Area 3 Leader, The University of Michigan **Nick Vlahopoulos** Associate Professor, The University of Michigan **Kyung K. Choi** Professor, The University of Iowa
3:45 - 4:00	**WRAP-UP AND Q & A** **Dennis Assanis,** Professor and ARC Director, The University of Michigan	
4:00	**ADJOURN**	

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Day 2, Wednesday , May 19, 2004 Schedule

7:30 - 8:00am **REGISTRATION AND CONTINENTAL BREAKFAST**

8:00 - 8:30 **WELCOME AND INTRODUCTION**

Dennis Assanis, Professor and ARC Director, University of Michigan
David Gorsich, Chief Scientist, National Automotive Center
Walter Bryzik, Chief Scientist, U.S. Army RDECOM-TARDEC

8:30 - 4:40pm **PARALLEL SYMPOSIA I–IV**
The balance of the day's activities is divided into **four** Parallel Symposia. They will run concurrent sessions concentrating on specific technical issues. A session matrix plan and abstracts of the technical presentations will be included to allow attendees to select from the various topics presented to match their technical interests.

Click here for Symposia Matrix

Abstracts will be posted soon.

Symposium I (abstracts)

1A Vehicle Dynamics & Proper Modeling

1B Vehicle & Driver Modeling

1C Fuel Cells

1D Imaging & Visualization

Symposium II (abstracts)

2A Design Optimization Under Uncertainty

2B Robustness and Trade-Off Analysis

2C Human Centered Design

2D Multi-Criteria Design Methodologies

Symposium III (abstracts)

3A Recent Progress in NVH Analysis

3B Vehicle-Terrain Interaction Modeling

3C Reliability Based Design Optimization

3D Vehicle System and Structural Design Methodologies

Symposium IV (abstracts)

4A Diesel Injection & Combustion

4B Advanced Diesel Engine Systems

4C Diesel Engine Modeling

4D Vehicle Component Modeling

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Day 2, Wednesday , May 19, 2004
Symposia Matrix

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Time	**Symposium I**	**Symposium II**	**Symposium III**	**Symposium IV**
	1A Vehicle Dynamics & Proper Modeling	**2A Design Optimization Under Uncertainty**	**3A Recent Progress in NVH Analysis**	**4A Diesel Injection & Combustion**
8.30 - 8.55	Using and Implementing the Milliken Moment Method for Analyzing Vehicle Handling	Theoretical Aspects of Optimization Under Uncertainty	Hybrid Finite Element Developments	Injection System Controls for Promoting Cold Starting and Low White Smoke Emissions
8.55 - 9.20	Combining the Milliken Moment Method and Dynamic Simulation to Evaluate Vehicle Stability and Controllability	An Efficient Single-Loop Method for Reliability-Based Design Optimization	Recent Progress in Reduced-Order Modeling of Vehicle NVH	Investigation of Advanced Injection Strategies for High Power Density and Low Emissions with Computational Fluid Dynamics
9.20 - 9.45	Determining Model Accuracy as a Function of Inputs and System Parameters	Design Optimization of Hierarchically Decomposed Multilevel Systems under Uncertainty	Probabilistic Vibration Analysis of Structures With Uncertainties	Experimental Demonstration of Dual-Use Engine Calibrations: Leveraging Modern Technologies to Meet Military Performance and Emissions Targets
9.45 - 10.10	System Partitioning for Improved Simulation-Based Design of Military Vehicles and Vehicle Subsystems	Uncertainty Propagation Techniques for Probabilistic Design of Multilevel Systems	Identification Methods of Lowest Eigenvalues for Finite Shell Model Using 7-Parameter Shell Formulation	Visualization and Luminosity Spectral analysis of Diesel Combustion: Effects of Injection timing, EGR, Swirl and Hydrogen Addition
10.10 - 10.30	**Break**			
	1B Vehicle & Driver Modeling	**2B Robustness and Trade-Off Analysis**	**3B Vehicle-Terrain Interaction Modeling**	**4B Advanced Diesel Engine Systems**
10.30 - 10.55	A Collision Warning Algorithm Based on Human Driving Data	Robust Design and Robust Control	Real-time Multibody Dynamic Simulation of Vehicles on Soft Terrain	Advanced Turbocharging and Power Assist Systems
10.55 - 11.20	Modeling, Analysis, and Control of a Four Wheel Steer-by-Wire System for Medium Duty Semi-Autonomous Ground Vehicles	Evaluation of Advanced Powertain Technologies with Emphasis on Fuel Economy and Emissions	Finite Element Modeling of Tire/Snow Interaction	Effect of Exhaust Gas Recirculation (EGR) in Examining the NOx versus Particulate Matter Emissions Tradeoff in a Heavy Duty Diesel Engine
11.20 - 11.45	Time Series Modelling of Testing Track Profiles	Model-Based Analysis of Performance Cost Tradeoffs for Engine Manifold Surface Finishing	Predictive Semi-analytical Models for Tire/Snow Interaction	Advanced Thermal Management for High Power Density Diesel Engine
11.45 - 1.00pm	**Lunch**			
	1C Fuel Cells	**2C Human Centered Design**	**3C Reliability Based Design Optimization**	**4C Diesel Engine Modeling**
1.00 - 1.25	Power Management of a Fuel Cell Vehicle	Torso Kinematics During Seated Reaches by Truck Drivers	Reliability-Based Design Optimization Using PMA+ & HMV+	A New Robust Observer for the Accurate Computation of the Instantaneous Total Engine Friction
1.25 - 1.50	Model Predictive Control for Current Regulation in a Hybrid Fuel Cell System	An Application of Digital Human Simulation to Aid in a Vehicle Maintenance Task Redesign	Performance Moment Integration Approach for Reliability-Based Robust Design Optimization	Lubrication Characteristics of the Bearings of High Power Density Diesel Engines
1.50 - 2.15	Fuel Cell Stack Membrane Humidity Model Validation	Shoulder Biomechanics and Proactive Interface Design Vibration Feedthrough Cancellation Using a Model Based Controller	New Dimension-Reduction Methods for Second-Moment and Reliability Analyses	Unsteady Convective Heat transfer Modeling and Application to the Intake Manifold of a Spark-Ignition Engine
2.15 - 2.40	Refined Thermal Model of Proton Exchange Membrane Fuel Cell	Evaluating Human In-Vehicle Reach Performance When Perturbed by Ride Motion	Primary Studies on Buckling and Crashworthiness Design with Multidisciplinary Objectives and Uncertainties in the System	Passive Thermal Management for Future Automotive Systems

2.40 - 3.00	**Break**			
	1D Imaging & Visualization	**2D Multi-Criteria Design Methodologies**	**3D Vehicle System and Structural Design Methodologies**	**4D Vehicle Component Modeling**
3.00 - 3.25	Multi-Sensor Data Fusion for Robot Mobility and Automotive Component Analysis	An Efficient Weighting Update Method to Achieve Acceptable Consistency Deviation in Analytical Target Cascading	Gluing Integration for Dynamics Simulation: Non-matching Interfaces and Mixed Models	Improved HE-HMMWV Component Models for Powertrain Control
3.25 - 3.50	3D Data Collection and Analysis of Vehicle Components	Preference Modeling in Multi-Criteria Engineering Design	An Implicit Integration Method for Sensitivity Analysis of Multibody Vehicle Dynamics	Modeling Aspects of Magtrans CVT
3.50 - 4.15	A Demonstration of Cooperative Mobility for Small Robotic Vehicles	Relevance of Epsilon-Pareto Solutions in Multi-Criteria Engineering Design	Design Sensitivity Analysis and Optimization of High Frequency Problems Using Energy Finite Element Method and Energy Boundary Element Method	Mesh Free Reverse Engineering of Automotive Components
4.15 - 4.40	Outdoor Scene Modeling Using a Mobile Multi-Sensor Platform	Design Configuration of Vehicle Components with Domain Knowledge Enhancement	Design and Optimization of Multi-Material Objects for Enhanced Thermal Behavior	A Shooting Algorithm for Adjoint Sensitivity Equations

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Day 2, Wednesday , May 19, 2004
Symposium Abstracts

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Symposium I

1A Vehicle Dynamics & Proper Modeling

Session Chair: Jeff Stein

1A1 **Using and Implementing the Milliken Moment Method for Analyzing Vehicle Handling**
Robert Hoffman, Dongsoo Kang, U. of Michigan
In the 1960's, William Milliken developed the Milliken Moment Method, which is a way of efficiently organizing the results from a constrained vehicle test. This research project used the MMM and dynamic simulation in a new way to evaluate vehicle stability and controllability. In the first presentation, the MMM will be reviewed as a general method for evaluating vehicle handling properties, and compared to other known metrics and tools that exist today. The relevant aspects of controllability, stability, and how they relate to the MMM will be reviewed. Lastly, the vehicle models that were used for implementing the MMM will be discussed. A Matlab generated model will be shown, as well as a new method for obtaining the MMM data from CarSim.

1A2 **Combining the Milliken Moment Method and Dynamic Simulation to Evaluate Vehicle Stability and Controllability**
Robert Hoffman, U. of Michigan
In the second presentation, the methodology used to combine the MMM and dynamic simulation will be described. In general, the MMM assesses the overall performance capability of the vehicle, and the simulation determines how much of that performance is used for a closed-loop maneuver. By mapping the simulation data onto the yaw moment – lateral acceleration diagram from the MMM, this method will allow a design engineer to explicitly quantify the tradeoff between the controllability and stability of a vehicle. Results from a design case study and comparison of the stability measure to phase plane analysis show that this method captures the tradeoff in design, and clearly represents the overall capability of the driver-vehicle system.

1A3 **Determining Model Accuracy as a Function of Inputs and System Parameters**
Bryon Sohns, U. of Michigan
Previous ARC research has developed an algorithm called AVASIM for assessing model validity systematically and quantitatively. AVASIM assess the validity of a model is based on a specific input and set of system parameters. The objective of this project is to define a Range of Validity of a model with respect to input and system parameter variations based on the AVASIM algorithm. A definition of, and procedure for evaluating the Range of Validity of a model based on the AVASIM algorithm is proposed and then demonstrated with three case studies. First a simple nonlinear mass-spring-damper system is linearized and evaluated. The Range of Validity of the model is established with respect to the size of an input step. A second case study linearizes a nonlinear transient vehicle-handling model. This system's accuracy is evaluated with respect to variation of two system parameters, resulting in a two-dimensional Range of Validity. Finally a complex nonlinear hydrogen fuel cell model developed within the ARC is linearized. This system's accuracy is evaluated with respect to two input parameters, with a resulting two-dimensional Range of Validity. The results show that the proposed procedure for assessing Model Range of Validity by using AVASIM is valid. The results from simulation agree well with what is expected for the various systems tested based on prior knowledge of the effects of linearization on model accuracy.

1A4 **System Partitioning for Improved Simulation-Based Design of Military Vehicles and Vehicle Subsystems**

Geoff Rideout, U. of Michigan

Mechanisms for removing unnecessary model complexity, and for verifying the validity of modeling assumptions as the system and environment change, are prerequisites for efficient and accurate simulation-based design of military vehicles. A partition search algorithm is presented that expands the scope of existing model reduction techniques developed in the ARC, and tracks the validity of simplifying assumptions based on decoupling. Negligible constraint equation terms are identified and eliminated based on power flow, resulting in local sites of one-way coupling between the input-output equations of generalized Kirchoff loops and nodes. If submodels are thereby created between which one-way coupling occurs, the model can be separated into "driving" and "driven" partitions that can be reduced and simulated independently. The algorithm is applied to an in-line six-cylinder engine to predict mount forces. In contrast to ad-hoc partitioned models based on assumption and intuition, the new partitioning method quantitatively identifies decoupling between reciprocating dynamics (driving) and block motion (driven). The decoupling intensity can be tracked as parameters and inputs change during the design process, and models of intermediate complexity can be automatically generated as decoupling erodes. The partitions can be simulated separately, and accurately predict mount forces with sizeable computational savings.

1B Vehicle & Driver Modeling

Session Chair: Huei Peng

1B1 **A Collision Warning Algorithm Based on Human Driving Data**

Huei Peng, U. of Michigan

Collision Warning/Collision Avoidance (CW/CA) systems are a major thrust of the Intelligent Vehicle Initiative identified by the US Department of Transportation. They are of interest to the Military because of the high number of fatalities associated with soldiers driving in their privately owned vehicles (POV). In addition, this active safety technique also form the foundation of safer convoy operations. Existing CW/CA literature mainly focus on algorithm development based on simple particle motions and human characteristics such as reaction delays. Evaluations of these algorithms were usually based on subjective ratings. A collision warning / collision avoidance system can be compared to a signal detection system distinguishing significant few from insignificant majority. From the view point of signal detection theory, it can be assumed that the whole traffic data we collected can be divided into two disjoint subsets and a CW/CA algorithm needs to decide whether the situation is safe or threatening by using a suite of measurements. Because of various reasons, such function would have two probability distribution functions for each subset. Four CW/CA algorithms reported in the literature--from researchers of Honda, Mazda, Jaguar and the Johns Hopkins University (JHU)--are evaluated against the identified data sets. The performance of these algorithms is determined through performance metrics commonly used in information retrieval under unbalanced data sets. In addition, using the separated data sets, we numerically search for the optimal parameter set for each of these algorithms. This study illustrates the potential of the "basis functions" used in these algorithms, as it is quite possible the original parameter sets have been tuned for consumers in a particular market and thus might not perform well by using the ICCFOT data. Finally, we conclude with proposing a new CW/CA algorithm that outperforms the algorithms discussed above.

1B2 **Modeling, Analysis, and Control of a Four Wheel Steer-by-Wire System for Medium Duty Semi-Autonomous Ground Vehicles**

Santosh Ancha, Abhijit Baviskar, Dr. John Wagner, and Dr. Darren Dawson, Clemson U.

Hybrid ground vehicles have motivated electric and steer-by-wire steering system technology due to restrictions on power source availability. Although these two steering systems are efficient, flexible, and environment friendly, the steer-by-wire system provides the opportunity for semi-autonomous and autonomous vehicle operation, as well as compliments a drive-by-wire architecture. An added advantage are the benefits derived, in terms of electronic tow-baring capabilities, convoy vehicle platooning functions, tele-operation of vehicles in hazardous conditions to minimize manpower requirements on field. For greater lateral vehicle performance, reduced maneuver transient time, and avoidance of undesirable vehicle motions through combined traction and steering control, a four wheel steering assembly with front and rear steering mechanism can uniformly control the wheels' steering angle depending upon the steering input. Mathematical models will be developed for a front and rear rack and pinion steer-by-wire system. Accompanying linear and nonlinear controllers will be designed for operator commanded tracking by adjusting the three servo-motor assemblies. Representative simulation results would be presented and discussed to support the evaluation of the four-wheel steering systems using various case studies for different steering maneuvers.

1B3 **Time Series Modelling of Testing Track Profiles**
T. C. Sun, Milton Chaika (Wayne State U.), David Gorsich (NAC)
Testing track profiles from Belgian Block and Perryman3 are studied. The Belgian Block data are tested to be linear, Gaussian and non-stationary but they behave like sample functions of a uniformly modulated process (i.e. the product of a deterministic function and a stationary process). The modeling of the profiles can be done by estimating the deterministic function and fit the stationary process with a well-known ARMA model. The Perryman3 data are tested to be non-Gaussian and non-stationary. First, the Box-Cox transformation is used to transform the data into a Guassian process. For some part of the profiles the transformation works while for other parts it does not. A second approach uses the intrinsic mode function (IMF) decompostion. The first intrinsic mode-function is found to be Gaussian which could be modeled and the first residue is non-Gaussian but is smoother and hence can be treated as a deterministic trend function. If it is necessary, the decomposition can be carried out one more time. The second intrinsic function still behaves like aGaussian process and the second residue is much smoother and can be approximated by a deterministic spline function. Work in this direction is still going on.

1C Fuel Cells

Session Chair: Anna Stefanopoulou

1C1 **Power Management of a Fuel Cell Vehicle**
Huei Peng, U. of Michigan
In this presentation, we will describe the modeling and design process for the power management control of a fuel cell hybrid vehicle (FCHV). First, subsystems of a FCHV are tested to obtain their dynamic and efficiency information. A SIMULINK model is constructed based on the sub-system information. Next, the design of the supervisory control algorithm of the FCHV is presented. In the literature, most of the control strategy developments rely on intuition and a heuristic methods to construct the controller, which often results in undesired characteristics such as cycle-beating and lack of a battery charge-sustaining strategy. This paper suggests the Stochastic Dynamic Programming (SDP) technique to solve the FCHV power management problem. The control law is in the form of stationary full-state feedback, which is directly implementable. Simulation results over standard driving cycles are presented to demonstrate the effectiveness of the proposed control strategy.

1C2 **Model Predictive Control for Current Regulation in a Hybrid Fuel Cell System**
Ardalan Vahidi and Anna Stefanopoulou, U. of Michigan
We formulate the distribution of current demand between the fuel cell and an ultra capacitor in a constrained optimization (model predictive control) framework. This work is motivated by the limitations that fuel cells face in following fluctuations in power demand. We show that the oxygen starvation was reduced from 50% in stand-alone FC architecture to less than 1% in the hybrid configuration during rapid load changes.

1C3 **Fuel Cell Stack Membrane Humidity Model Validation**
Denise McKay, U. of Michigan
We will present an experimentally validated model for estimating electrode relative humidity of a proton exchange membrane fuel cell (PEMFC) stack. The model and experimental procedure can be used in conjunction with an estimation algorithm in real-time without expensive measurements that require unrealistic stack instrumentation impractical for commercial fuel cell applications. The long term goal is to develop a systematic procedure for warming up and humidifying PEMFC stacks prior to connection of a load.

1C4 **Refined Thermal Model of Proton Exchange Membrane Fuel Cell**
Sangseok Yu, Dohoy Yung, Dennis N. Assanis, U. of Michigan
A numerical model for PEMFCs (proton exchange membrane fuel cells) was developed to simulate mass and heat transport of PEMFCs. The model includes sub-models for an electric conductivity of the membrane electrolyte, a reaction at the cathode catalyst layer, heat transfer and thermal management. For the electric conductivity of the membrane electrolyte, water transport model based on the water activities at anode and cathode side is employed. The model predicted mass transport limitation at high current density with agglomerate cathode catalyst layer. Two-dimensional heat transfer is assumed for the thermal management and heat transfer model. The model was validated with published experimental data over various cell temperature. For the transportation application, it is necessary to develop large size high performance PEMFCs. Especially, the mathematical model shows that the performance and efficiency of large size PEMFCs are more closely connected with thermal management as the size is increased. It is also found that performance of PEMFCs is significantly affected by the local hot spot resulting in low relative humidity within the fuel cell or fuel

cell stack in case of large size PEMFCs. When the large cells operated at low humidity condition, it results in low electric conductivity of membrane electrolyte and finally low performance and efficiency. The model also shows the cathode overpotential and electric conductivity are varied with channel downstream even though cell is operated with isothermal assumption. Therefore, to achieve high performance commercial PEMFCs, it is required to employ efficient cooling for heat management and efficient feeding channel for supply of reactant and oxidant.

1D Imaging & Visualization

Session Chair: Andreas Koschan

1D1 **Multi-Sensor Data Fusion for Robot Mobility and Automotive Component Analysis**

Faysal Boughorbel, U. of Tennessee

Registering multiple images is an important first step in object modeling and recognition tasks. In our research we address the problem of 3D and 2D registration of free-form shapes, the main contribution being the design of a physics-inspired matching criterion which is differentiable and convex in a large neighborhood of the aligned position. Our main motivation was the limitations of standard techniques, and in particular the Iterative Closest Point algorithm (ICP). For instance, the non-differentiable cost function associated with ICP imposes a locally convergent scheme that requires close initialization. In real applications the preliminary point-feature extraction and matching step are necessary before proceeding with the ICP refinement step. In this research we use a straightforward criterion consisting of an integration of Gaussian force fields that depend on distances and point attributes, such as local moment invariants computed from the datasets. We show that this criterion can be used for registering imagery acquired by different sensors. This approach ensures convexity in the neighborhood of the solution, as well as continuous differentiability, allowing for the use of a wide range of well proven optimization techniques. More importantly, the criterion can be evaluated, with linear complexity, using the recent numerical technique known as the Fast Gauss Transform, making it computationally less expensive than current registration algorithms.

1D2 **3D Data Collection and Analysis of Vehicle Components**

Rangan Sukumar, U. of Tennessee

Our research efforts focus on the construction of a scanning mechanism that would be able to create 3D models of automotive components. We make use of the sheet of light active range imaging technique for this task and extend its capability to extract geometry of automotive parts. In this presentation, we outline our design efforts towards data collection and follow it up with results on 3D model creation and analysis of objects. We present experimental results of an information theory-based surface shape description algorithm on the laser scanned 3D models. The 3D data acquisition process to generate a dense point cloud of a particular view of an object, multiple view fusion and surface graph representation (comparable to CAD) of the models is our implementation of a pipeline that aids reverse engineering and inspection.

1D3 **A Demonstration of Cooperative Mobility for Small Robotic Vehicles**

Ashish D Deshpande, U. of Michigan

Physical cooperation among small vehicles is a solution to improving their mobility on rough terrain. We are developing a system of a pair of small vehicles that cooperate to cross a gap. In past, we carried out static analysis of the system that provides guidelines for design improvements. We demonstrate the working of this system with hardware implementation. We have used two toy sized tanks (about 15 inches long) and have designed a mechanism which facilitates cooperation without additional actuation. The control laws are designed analytically based on a model of the vehicles and are implemented with an OOPic microcontroller. The hardware implementation demonstrates that a simple, low cost system can built to achievephysical cooperation among small vehicles to improve mobility. In addition, we have developed control laws which exploit the vehicle dynamics to facilitate physical cooperation to relaxing the design constraints.

1D4 **Outdoor Scene Modeling Using a Mobile Multi-Sensor Platform**

Brad Grinstead, U. of Tennessee

The objective of this research is to provide accurate and detailed models of a variety of large-scale outdoor environments that are suitable for a number of simulation tasks. We have developed a mobile system that acquires the 3D geometry and color texture information necessary to quickly and accurately digitize these large-scale environments. Ground-level terrain geometry is acquired with an accurate short-range laser scanner, while above ground geometries are digitized via a long-range laser scanner. Texture information is acquired with high-resolution digital cameras. Pose estimation for each data sample is calculated by fusing the information from various instruments including GPS, INS, and video. The entire sensor package is mounted on a vehicle that moves past the environment to be scanned at normal driving speeds, providing a fast and easy method for acquiring the necessary data. Once the data is acquired, a variety of post-processing algorithms are applied to fill holes, reduce noise effects, and to develop multi-resolution models sufficient to the application at hand. This system has been tested in the field, and the generated models are accurate in terms of both geometry and visual perception, and thus are appropriate for use in populating a virtual environment for a variety of simulation and testing tasks.

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Symposium II

2A Design Optimization Under Uncertainty

Session Chair: Panos Papalambros

2A1 **Theoretical Aspects of Optimization Under Uncertainty**
K.Y. Chan and P.Y. Papalambros, U. of Michigan
Design optimization under uncertainty is the activity considering the variability of the design due to various sources of uncertainties. In this paper, the definition of constraint activity and the approaches for monotonicity analysis in deterministic design optimization are both extended to the case where the design variability exists. Based on the input probability density functions, the correlation of the uncertainties and the desired level of system reliabilities, we construct the variability contours as boundaries that design realization will not exceed at desired reliability level. Once the variability contours are formed, active constraints are defined as the constraints that are tangent to the variability contour and have non-zero Lagrange multipliers. After understanding the meaning of constraint activity in the probabilistic design, we found that the monotonicity analysis in the traditional optimization can be adapted to probabilistic design under the assumption that the original deterministic constraints are consistent with respect to the variability contour. From the demonstrated example, we show that understanding the constraint activity and perform monotonicity analysis have great advantage to reduce the complexity of the design problems under uncertainty.

2A2 **An Efficient Single-Loop Method for Reliability-Based Design Optimization**
Jinghong Liang, Zissimos P. Mourelatos (Oakland Univ.) Jian Tu (GM R&D Center)
Reliability-Based Design Optimization (RBDO) can provide optimum designs in the presence of uncertainty. It can therefore, be a powerful tool for design under uncertainty. The traditional, double-loop RBDO algorithm requires nested optimization loops, where the design optimization (outer) loop, repeatedly calls a series of reliability (inner) loops. Due to the nested optimization loops, the computational effort can be prohibitive for practical problems. A single-loop RBDO algorithm is proposed in this paper for both normal and non-normal random variables. Its accuracy is the same with the double-loop approach and its efficiency is almost equivalent to deterministic optimization. It collapses the nested optimization loops into an equivalent single-loop optimization process by imposing the Karush-Kuhn-Tucker optimality conditions of the reliability loops as equivalent deterministic equality constraints of the design optimization loop. It therefore, converts the probabilistic optimization problem into an equivalent deterministic optimization problem, eliminating the need for calculating the Most Probable Point (MPP) in repeated reliability assessments. Several numerical applications including an automotive vehicle side impact example, demonstrate the accuracy and superior efficiency of the proposed single-loop RBDO algorithm.

2A3 **Design Optimization of Hierarchically Decomposed Multilevel Systems under Uncertainty**
M. Kokkolaras, P.Y. Papalambros, U. of Michigan), Z.P. Mourelatos (Oakland U.)
We present a methodology for design optimization of decomposed systems in the presence of uncertainties. We extend the analytical target cascading (ATC) formulation to probabilistic design by treating stochastic quantities as random variables and parameters and posing reliability-based design constraints. We model the propagation of uncertainty throughout the multilevel hierarchy of elements that comprise the decomposed system by using the advanced mean value (AMV) method to generate the required probability distributions of nonlinear responses. We utilize appropriate metamodeling techniques for simulation-based design problems. A simple yet illustrative hierarchical bi-level engine design problem is used to demonstrate the proposed methodology.

2A4 **Uncertainty Propagation Techniques for Probabilistic Design of Multilevel Systems**

Byeng D. Youn, K.K. Choi (U. of Iowa), M. Kokkolaras, P.Y. Papalambros (U. of Michigan), Z. Mourelatos (Oakland U.), David Gorsich (NAC)

Multilevel system design refers to the optimization process of large, complex engineering systems that are decomposed into a hierarchy of coupled subsystems. Analytical target cascading (ATC) is a methodology that takes these interactions into account during the early stages of the design optimization process. In recent years, design guidelines and standards are being adjusted to incorporate the concept of uncertainty into the early design and product development stage. In response to these new requirements, the ATC formulation has been extended to solve probabilistic design optimization problems. Probabilistic design of multilevel systems does not only entail the difficulty of solving non-deterministic optimization problems; it is also quite challenging to model the mechanism of uncertainty propagation throughout the multilevel hierarchy. In previous work, the first-order Taylor expansion method was shown to exhibit relatively large errors in approximating statistical moments estimate of nonlinear responses, and to have a slow convergence rate of the ATC process due to a small variation required. This presentation suggests two alternative methods for estimating statistical moments of nonlinear responses of random variables: using approximate probability density functions to be numerically integrated and using numerical quadrature rules motivated by Taguchi-type experimental designs. The second method is called performance moment integration (PMI), which is successfully applied to the reliability-based robust design optimization by estimating statistical moments effectively. The scope of this presentation is to determine which type of multi-level system applications each method is best suited for, based on its numerical aspects.

2B Robustness and Trade-Off Analysis

Session Chair: Zissmos Mourelatos

2B1 **Robust Design and Robust Control**

S. Alyaqout and P.Y. Papalambros, U. of Michigan

As part of an effort to improve the robustness properties of systems, the present study presents an approach that combines robust design with robust control. Traditionally, the robust control problem is solved sequentially by optimizing the design first then improving the robustness using robust control methods. The new formulation modifies this sequential approach by adding a robust design objective and proposing an integrated optimization process. Several optimization strategies are compared and the complexity associated with uncertainty propagation between design and control is studied. As expected, results show improvement in robustness of the overall system at the expense of overall system performance. However, the robust system maintains good performance. The proposed approach yields better performance of the combined system as opposed to optimizing design and control individually.

2B2 **Evaluation of Advanced Powertain Technologies with Emphasis on Fuel Economy and Emissions**

E. Rask, R. Fellini, and P.Y. Papalambros, U. of Michigan

The goal of most advanced powertrains is reduce fuel consumption and emissions while remaining within acceptable performance limits. While it is often desired to reduce both emissions and fuel consumption, these objectives are often optimal at different configurations. Additionally, these improvements in “environmental performance” may have a varying effect on “driving performance.” This case study seeks to evaluate various advanced engine types in terms of their ability to improve fuel economy and reduce emissions. Additional analysis will investigate the tradeoffs associated with these various improvements and their relationships to driving performance. In summary, this work seeks to investigate the possible improvements created by a certain engine technology as well as select an optimal technology which represents the best compromise between the various objectives of fuel economy, emissions, and performance.

2B3 **Model-Based Analysis of Performance Cost Tradeoffs for Engine Manifold Surface Finishing**

Z. Li, P. Georgiopoulos, and P.Y. Papalambros, U. of Michigan

The link between manufacturing process and product performance is studied in order to construct analytical, quantifiable criteria for the introduction of new engine technologies and processes. Cost associated with a new process must be balanced against increases in engine performance and thus demand for the particular vehicle. In this work, the effect of the Abrasive Flow Machining (AFM) technique on surface roughness is characterized through measurements of specimens, and a predictive engine simulation is used to quantify performance gains due to the new surface finish. Subsequently, economic cost-benefit analysis is used to evaluate manufacturing decisions based on their impact on firm's profitability. A demonstration study examines the use of AFM for finishing the inner surfaces of intake manifolds for two engines, one installed in a compact car and the other in an

SUV.

2C Human Centered Design

Session Chair: Don Chaffin

2C1 **Torso Kinematics During Seated Reaches by Truck Drivers**
Matthew P. Reed, Matthew B. Parkinson, U. of Michigan
Simulations of humans performing seated reaches require accurate descriptions of the movements of the body segments that make up the torso. Data to generate such simulations were obtained in a laboratory study using industrial, auto, and truck seats. Twelve men and women reached to push-button targets located throughout their right-hand reach envelopes as their movements were recorded using an electromagnetic tracking system. The data illustrate complex patterns of motion that depend on target location and shoulder range of motion. Pelvis motion contributes substantially to seated reach capability. Torso kinematics from the truck seat were combined with a previously developed reach difficulty model for truck and bus drivers to assess the relationships between reach difficulty and torso kinematics.

2C2 **An Application of Digital Human Simulation to Aid in a Vehicle Maintenance Task Redesign**
Don B. Chaffin, Kevin Rider, James Foulke, U. of Michigan
Maintenance of Army vehicles often depends on designing hardware that can accommodate a large amount of variation in human capabilities. Digitial human simulation represents a growing technology that can assist a designer in the assessment of alternative proposed hardware designs without the need and expense to build and test alternative hardware designs. This paper reviews a well recognized human problem associated with the existing design of the FMTV regarding battery removal and replacement. The present battery handling task is evaluated with existing digital human modeling tools. Several alternative vehicle design changes are proposed. These new designs are evaluated using digital human modeling methods to determine the affects that each would have on alleviating the human performance problems that exist today.

2C3 **Shoulder Biomechanics and Proactive Interface Design**
Clark R. Dickerson, U. of Michigan
The shoulder is the primary joint responsible for the range of motion of the upper arm, and as a result, the hand. To investigate the interactions between operators and machines at the interface, mathematical biomechanical models have been generated to describe both general and specific tissue loading in the shoulder. Further, statistical models that evaluate the perception of difficulty associated with task performance have been developed. The evolution of creating useful models has continued with early-stage integration of these models with commercially available digital human simulation software. The realization of shoulder models working in a simulation environment will allow the proactive evaluation of interface design changes early in the product/interface design cycle, as it enables the analysis and evaluation of multiple design permutations and associated changes in joint and tissue loading, as well as operator comfort.

2C4 **Vibration Feedthrough Cancellation Using a Model Based Controller**
Szabolcs Sovenyi, U. of Michigan
Human operators (HO) controlling vehicles or other pieces of equipment inside moving vehicles with a joystick impose unintended forces on the joystick due to vehicle accelerations. If the controlled equipment is not the vehicle, these forces may degrade continuous tracking performance, and if it is, they may cause undesired oscillations that may jeopardize the safe operation of the vehicle. The aim of this project is to compensate the unintended forces using a motorized joystick and a cancellation controller. The cancellation controller is based on a model of the human biomechanical system, and it estimates the biomechanical force the HO imposes on the joystick based on vehicle acceleration measurements. The HO is modeled as a Thevenin equivalent force generator with the joystick being a load impedance. The Thevenin equivalent is a series connection of an internal mechanical impedance and an ideal effort generator modulated by vehicle accelerations. This simple model leads to a method of identifying the biomechanical system of the HO using a three degree-of-freedom lumped parameter mass-spring-damper model and a test protocol. A frequency domain parameter search algorithm is used to find the parameters of the lumped parameter model, which then yields the cancellation controller. Experimental results demonstrate that the controller improves tracking performance and suppresses oscillations.

2C5 **Evaluating Human In-Vehicle Reach Performance When Perturbed by Ride Motion**
Kevin A. Rider, Don B. Chaffin, Matthew P. Reed, U. of Michigan
Continual advancements in technology are placing increasing information and power at the fingertips of vehicle operators. In a stationary environment, common in-vehicle reaching tasks can be performed

with relative ease. However performing these same tasks under terrain-induced ride motion often requires significantly increased dexterity. Thorough understanding of the human performance degradation of in-vehicle reaching tasks is required to adequately design the increasingly complex control displays and navigation systems. Ongoing research is being conducted utilizing the Ride Motion Simulator (RMS) at the US Army's Tank-Automotive Research, Developments, and Engineering Center (TARDEC) to determine appropriate criteria for the design and layout of vehicle controls and displays. Most recently, the RMS was used to simulate a HMMWV traveling off-road, while seated occupants performed push-button reaching tasks to three touchpanel displays. Thirty-nine target locations were used, where either physical buttons were located or virtual targets were displayed on the touchpanel. Researchers are principally interested in determining the biomechanical, neuromuscular, and perceptual-motor components that result in increased movement time and decreased accuracy of push-button reaches under vehicle motion. Models of reaching under ride motion scenarios will be useful in designing future vehicle suspension and seating systems to cancel the adverse affects of particular ride motions.

2D Multi-Criteria Design Methodologies

Session Chair: Georges Fadel

2D1 **An Efficient Weighting Update Method to Achieve Acceptable Consistency Deviation in Analytical Target Cascading**

J. Michalek and P.Y. Papalambros, U. of Michigan

Weighting coefficients are used in Analytical Target Cascading (ATC) at each element of the hierarchy to express the relative importance of matching targets passed from the parent element and maintaining consistency of linking variables and consistency with designs achieved by subsystem child elements. Proper selection of weight values is crucial when the top level targets are unattainable, for example when "stretch" targets are used. In this case, strict design consistency cannot be achieved with finite weights; however, it is possible to achieve arbitrarily small inconsistencies. We present an iterative method for finding weighting coefficients that achieve solutions within user-specified inconsistency tolerances and demonstrate its effectiveness with several examples. The method also led to reduced computational time in the demonstration examples.

2D2 **Preference Modeling in Multi-Criteria Engineering Design**

Brian J. Hunt, Vincent Blouin, and Margaret M. Wiecek, Clemson U.

Multi-criteria engineering design requires elicitation of the designer's preferences that are used in the selection of a preferred design. Such preferences are typically defined and utilized after finding the Pareto efficient designs for the problem. We investigate ways to model the designer's preferences and implement them in an optimization process that directly generates preferred efficient solutions. This ensures that the optimization process does not yield efficient designs that would ultimately be eliminated from consideration because they do not satisfy the designer's preferences. In particular, we study two preference modeling frameworks and discuss their use in this context. Although our results have been established for any number of criteria, we demonstrate our methodology on a tri-criteria tractor-trailer design problem.

2D3 **Relevance of Epsilon-Pareto Solutions in Multi-Criteria Engineering Design**

Alexander Engau (speaker), Vincent Y. Blouin, Margaret M. Wiecek, and Brian J. Hunt, Clemson U.

Although Pareto optimality has contributed to the success of multi-criteria design and opened up possibilities for multi-facet enhancements of the design process, many methodological and numerical issues remain to be resolved. One of them is the assessment of sensitivity and robustness of designs allowing for minor inaccuracies during the production process without critical consequences on the final design and the overall performance. We use the concept of epsilon-Pareto optimality and develop an approach to measuring the sensitivity of designs in the design space by investigating the effects of slight variations of the optimal performance criteria, traced back to the corresponding designs. This enables us to extend the set of possible solutions and to identify more robust designs whose performance may be chosen arbitrary close to optimality. Illustrative examples are included.

2D4 **Design Configuration of Vehicle Components with Domain Knowledge Enhancement**

Yi Miao (speaker), Vincent Y. Blouin, and Georges M. Fadel, Clemson U.

The goal of configuration design and packaging optimization is to find the optimal placement of a set of objects in a system while satisfying functional requirements and minimizing criteria. This presentation gives out the latest development of solving packaging optimization problems using Multi-Objective Genetic Algorithm. The method has been applied to the vehicle configuration design, in which three objectives are considered: vehicle dynamic behavior, maintainability and survivability. A swap operator specially constructed for the packaging problem has been incorporated in this method as the domain knowledge enhancement. The performance of the method is then systematically compared to the conventional method with respect to its ability in generating the Pareto front for the multi-criteria design problem. Other work in progress on the development of the packaging and configuration design methodology will be presented.

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Symposium III

3A Recent Progress in NVH Analysis

Session Chair: Christophe Pierre

3A1 **Hybrid Finite Element Developments**

Nick Vlahopoulos, U. of Michigan

In previous years the basic theory for the hybrid FEA method was developed.It enables to couple conventional FEA with Energy FEA (EFEA) in order to model the vibrational behavior of vehicle structures in the mid-frequency range. The EFEA has been developed and validated through comparison to test data for computing the high frequency vibration of naval and aerospace structures. Some of the completed validation results will be presented. The hybrid FEA has been utilized for computing the structural vibration of a typical automotive body-in-white. The hybrid FEA results and the required computational time are compared to the results produced by a very dense conventional FEA model. Finally, the new effort of transitioning these developments into high frequency shock vibration simulations of Army vehicles due to blast/impact type of loads will be discussed. This new capability will allow assessing equipment failure due to blast/impact loads.

3A2 **Recent Progress in Reduced-Order Modeling of Vehicle NVH**

Geng Zhang, Matthew P. Castanier, and Christophe Pierre, U. of Michigan

Finite element analysis combined with component mode synthesis (CMS) is an effective tool for the analysis of vehicle noise, vibration, and harshness (NVH) at low frequencies. However, when the frequency range of interest is increased, or if the effects of design changes or uncertain system parameters are considered, then the computational costs of this approach can become prohibitive. In previous research, a component-interface reduction method was developed to obtain more compact reduced-order models for vehicle NVH problems. By applying this reduction technique, an extensive vibration and power flow analysis was successfully carried out on a large structural model of a sport utility vehicle. In this presentation, three key advances are highlighted from recent research on this topic. First, a filtration technique is applied to the CMS constraint modes in order to significantly reduce the computation time required to generate a reduced-order model. Second, quasi-static constraint modes and corresponding quasi-static interface modes are employed to produce a more compact and accurate model for a targeted frequency band. Third, a parametric reduced-order modeling procedure is used to enable the efficient evaluation of the influence of design changes and parameter uncertainties on vibration response. Applications to vehicle structural models will be used to illustrate the performance of these methods.

3A3 **Probabilistic Vibration Analysis of Structures With Uncertainties**

Soo-Yeol Lee, Matthew P. Castanier, and Christophe Pierre, U. of Michigan

Structural vibration can be strongly affected by uncertainties such as manufacturing tolerances, variations in material properties, etc. In such cases, a probabilistic approach is needed. In this presentation, four probabilistic methods from the reliability engineering literature will be examined in terms of their applicability and efficiency for vibration problems: (1) a first-order reliability method (FORM), (2) a second-order reliability method (SORM), (3) an advanced mean value (AMV+) method, and (4) a response surface method (RSM) using a moving least squares approach. It will be shown that the performance of each probabilistic method is highly dependent on the shape of the limit-state surface in the uncertainty space. For some cases featuring nonlinear limit-state surfaces, reliability methods fail to give probabilistic predictions with accuracy and efficiency, and thus alternative or specialized techniques are needed. Examples will be shown for a general engineering structure and for a structure with high sensitivity to uncertainties.

3A4 **Identification Methods of Lowest Eigenvalues for Finite Shell Model Using 7-Parameter Shell Formulation**

Youngwon Hahn, Noburu Kikuchi, U. of Michigan

Two eigenvalue extraction methods and finite shell element methods are studied. For finite shell element methods, 7-parameter shell formulation are considered. Discrete Shear Gap (DSG) shell element and mixed element for 7-parameter shell formulation are also discussed. For the identification methods of eigenvalues, two new computational methods for large-scale finite shell element model are proposed; one is called Numerical Modal Test (NMT) and the other is called Frontal Stabilized Block Subspace Iteration method (FSBSI). NMT has numerical procedure similar to experimental modal test. Peak-picking by Fast Fourier Transform (FFT) and Frequency Domain Decomposition (FDD) are used to detect eigenvalues from time history data of FE results. FSBSI is modified Block Subspace Iteration method. For more accurate and reliable simulation, M-orthogonalization scheme is inserted into original Subspace Iteration algorithm and Frontal method is used for the inverse calculation for efficient memory control.

3B Vehicle-Terrain Interaction Modeling

Session Chair: Zheng-Dong Ma

3B1 **Real-time Multibody Dynamic Simulation of Vehicles on Soft Terrain**

Weidong Pan and L.D. Chen, U. of Iowa

This paper presents an approach to real-time multibody dynamic simulation of vehicles on soft terrain. High fidelity, multibody dynamics approach is employed for vehicle modeling so that vehicle nonlinear dynamic characteristics can be reliably predicted under realistic off-road conditions. High fidelity terrain model is developed to support accurate terra-mechanics computation and to capture the permanent effects of vehicle on environment such as ruts. Tire-soil interaction is modeled using a hybrid approach of empirical and semi-empirical models where an extended and virtually validated Bekker-Wong soil model is included. The above mentioned components are integrated to form a complete real-time simulation environment for mobility analysis of vehicles on soft terrain. The proposed approach is demonstrated via an example. Conclusions and future research directions are presented at the end of the paper.

3B2 **Finite Element Modeling of Tire/Snow Interaction**

Jonah Lee, U. of Alaska, Fairbanks

The interaction between a pneumatic tire and deformable terrain such as unpaved ground or snow has a great impact on the design and dynamic performance of an off-road vehicle. The general-purpose finite element program, ABAQUS, was used to conduct the simulation and to calculate tire forces as a function of the longitudinal slip, slip angle and slip with a camber angle. A finite element model of a Goodyear Wrangler tire HT235/75R15 was built and used in the simulation. The tire model was tested numerically on a rigid surface for its overall mechanical behavior and the results were compared with experimental data in the deflection, contact area, contact stress, and deformation profile of the tire under different inflation pressures with good agreement. Tire/snow interaction simulations were then conducted and the results were compared with limited experimental data with good agreement. These finite element results will be used to construct empirical equations of traction versus longitudinal slip, slip angle, and camber angle, which could be used in vehicle dynamics.

3B3 **Predictive Semi-analytical Models for Tire/Snow Interaction**

Jonah Lee, U. of Alaska, Fairbanks

The interaction between a pneumatic tire and deformable terrain such as soil, ice or snow has a great impact on the design and dynamic performance of an off-road vehicle. We are developing predictive semi-analytical models for tire/snow interaction. Our initial modeling approach is to adapt existing on-road tire/terrain predictive models for the interface between the deformable tire and fresh snow and investigating the effects of fresh snow on tire-snow interaction forces. The slip is considered a function of the direction of slip velocity and the friction coefficient is adjusted by taking the snow material parameters into account. The tire/snow tangential resultant forces versus longitudinal slip and slip angle will be presented. Results will also be compared with those for different types of terrain. The sparsity of experimental tire/snow interaction data necessitates the estimate of certain parameters. We expect our models to improve in methodology as well as in accuracy in the near future by incorporating more experimental data as well as a statistical representation of the properties of snow. Future work would include incorporating the models in vehicle dynamics programs to understand the effect of snow terrain on vehicle mobility, stability and control.

3C Reliability Based Design Optimization

Session Chair: K. K. Choi

3C1 **Reliability-Based Design Optimization Using PMA+ & HMV+**

K.K. Choi, Byeng D. Youn, and Liu Du, U. of Iowa

This presentation describes recently developed enriched performance measure approach (PMA+) and refined hybrid mean value method (HMV+) for reliability-based design optimization (RBDO) to improve computational efficiency and stability. Three features of PMA+ are presented: as a way to launch RBDO at a deterministic optimum design; as an efficient probabilistic feasibility check; and as a fast reliability analysis under the condition of design closeness. Starting RBDO at a deterministically optimized design improves numerical efficiency by reducing the number of RBDO iterations. During RBDO, a significant computational burden is imposed on the feasibility analysis of design constraints due to expensive reliability analysis. Such difficulties can be resolved by using the mean value (MV) first-order method with an allowable accuracy for the purpose of effective feasibility identification using an e-active strategy. This feasibility check will reduce the number of required reliability analyses. Once e-active and violated constraints of the RBDO problem are identified, reliability analysis is carried out by using the refined hybrid mean value method (HMV+). HMV+ is developed to improve the original HMV method, in terms of stability and efficiency for highly nonlinear performance functions by confirming a convergent behavior at each iteration of the reliability analysis. Finally, a fast reliability analysis method is proposed by reusing some of the information obtained at the previous RBDO iteration to efficiently evaluate probabilistic constraints at the current design iteration under the condition of design closeness. Effectiveness of the proposed PMA+ and HMV+ is compared to existing RBDO methods from a numerical efficiency and stability point of view using several numerical examples.

3C2 **Performance Moment Integration Approach for Reliability-Based Robust Design Optimization**

Byeng Dong Youn, K. K. Choi, and Liu Du, U. of Iowa

Reliability-based robust design optimization deals with two objectives of structural design methodologies subject to various uncertainties: reliability-based design and robust design. A reliability-based design optimization deals with the probability of failure, while a robust design optimization minimizes the product quality loss. In general, the product quality loss is described by using the first two statistical moments: mean and standard deviation. In this presentation, a performance moment integration (PMI) method is proposed by using numerical integration scheme for output response to estimate the product quality loss. Three-point numerical quadrature technique is used for numerical integration scheme to approximate the statistical moments of output response accurately. The PMI method is shown to effectively assess the quality loss of the product and to perform reliability-based robust design optimization in an efficient manner. As well, the proposed method resolves the burden of a second-order sensitivity required for design optimization in the worst-case method or root sum square method using a Taylor series for statistical moment calculation. For the reliability part of the reliability-based robust design optimization, the enriched performance measure approach (PMA+) and its numerical method, refined hybrid-mean value (HMV+) method, is used. New formulations of reliability-based robust design optimization are presented for three different types of robust objective, such as smaller-the-better (S-Type), larger-the-better (L-Type), and nominal-the-better types (N-Type). Examples are used to demonstrate the effectiveness of reliability-based robust design optimization using the proposed PMI method for different types of robust objective.

3C3 **New Dimension-Reduction Methods for Second-Moment and Reliability Analyses**

S. Rahman and H. Xu, U. of Iowa

A new class of computational methods, referred to as dimension-reduction methods, has been developed for predicting statistical moments and reliability of mechanical systems subject to random loads, material properties, and geometry. The methods involve an additive decomposition of an N-dimensional response function into at most S-dimensional functions, where S ? N; an approximation of response moments by moments of input random variables; and a moment-based quadrature rule for numerical integration. A new theorem is presented, which provides a convenient means to represent the Taylor series up to a specific dimension without involving any partial derivatives. The proposed methods require neither the calculation of partial derivatives of response, as in commonly-used Taylor expansion/perturbation methods, nor the inversion of random matrices, as in the Neumann expansion method. Using these dimension-reduction methods, approximate values of a performance function at arbitrarily large number of input can be generated, enabling subsequent response surface approximation and Monte Carlo simulation efficiently. Due to a small number of function evaluations, the proposed methods are very effective, particularly when a response evaluation entails costly finite element or other numerical analysis. Several numerical examples involving elementary mathematical functions and solid-mechanics problems are presented. Results indicate that the dimension-reduction methods generate convergent solutions and provide more accurate and efficient estimates of statistical moments than existing methods. Furthermore, the proposed methods provide accurate and computationally efficient estimates of reliability.

3C4 **Primary Studies on Buckling and Crashworthiness Design with Multidisciplinary Objectives and Uncertainties in the System**

Chang Qi, Z.-D. Ma, N. Kikuchi, C. Pierre, U. of Michigan

In this presentation, we will consider fundamental principles of buckling and crashworthiness design, especially with other design objectives (such as durability and NVH) and uncertainties in mind. Uncertainties can be classified into three categories: parameter uncertainties, modeling uncertainties, and uncertainties in the loading and boundary conditions. Uncertainties will have great effects on the results obtained from a deterministic buckling or crash analysis, and it may change the nature and fundamental phenomena of the prediction. We will discuss this through examples. Another issue to be discussed is the relationship between buckling and crashing. Buckling modes have been used to design a structure for crashworthiness, but crashing is not equal to buckling. Structure may fail under the load far below the critical buckling load. We will also discuss this through examples. In the study of vehicle crashworthiness, design of a structure against buckling failure is an important issue. Desired critical buckling loads and buckling modes can be achieved through design optimization including size, shape and topology; this will be the objective of this research. Besides the stability target, durability and NVH targets can also be included resulting in a multidisciplinary design optimization problem. Currently, design against buckling (DAB) of a general purpose mounting system has been studied to investigate the essences of the physical problem, considering the uncertainties mentioned above. The general purpose mounting system can represent an engine mounting system or a cabin-frame mounting system, etc. Multidisciplinary design optimization of a real engineering application in an innovative hydraulic-hybrid vehicle is used as an example to demonstrate the design targets mentioned above.

3D Vehicle System and Structural Design Methodologies

Session Chair: Gregory Hulbert

3D1 **Gluing Integration for Dynamics Simulation: Non-matching Interfaces and Mixed Models**

J. Wang, P. Adamczyk, Z.-D. Ma, G.M. Hulbert, U. of Michigan

There is a great need for developing methodologies that can be exploited to simulate mechanical systems whose models are distributed amongst disparate production units. Such methodologies need to maintain simulation fidelity, must be efficient and must maintain the “privacy” of the individual component models amongst potentially competing units in the supply chains. Our previous ARC presentations have demonstrated a flexible and general distributed-simulation platform that can incorporate functionally and geographically distributed subsystems models for virtual prototyping, across a network, e.g., Internet, of mechanical systems. This platform has two major features: first, allow the subsystems models to be developed independently and to be distributed in different computing units; second, allow the model developers to protect their proprietary information by not exposing internal information of their models. In this presentation, we will discuss our recent progress with a focus on the issues such as coupling models with non-matching interfaces and integration of multidisciplinary models across a network. In general, the independently developed subsystems models may have different numerical representations, they may be solved using different solution methods and especially they may have non-matching interfaces representations for the glue process. For example, different coordinate systems and different finite element meshes may be used for different subsystems models. Interfaces exposed by different subsystems models are not necessary to have the consistent nodes that can be easily assembled (glued) together. In this presentation, we will discuss basic ideas and methods for how to glue the interfaces with non-matching representations, especially non-matching meshes and nodes. Several examples will be given to demonstrate the feasibility and generality of the gluing algorithm developed. Furthermore, the integration of multidisciplinary subsystems models will be discussed with a presentation of preliminary results from gluing a multibody dynamics vehicle model and a finite element terrain model.

3D2 **An Implicit Integration Method for Sensitivity Analysis of Multibody Vehicle Dynamics**

Xicheng Wang, Edward Haug, and Weidong Pan, U. of Iowa

An implicit Runge-Kutta integration method is presented for design sensitivity analysis of multibody vehicle dynamics. The method is based on the generalized coordinate partitioning algorithm for DAE solution and the direct differentiation method for design sensitivity. In this method, implicit integration formulas are used to express design sensitivity of independent generalized coordinates and their first time derivative as functions of design sensitivity of independent accelerations at discrete integration time grids. The set of state-space, second-order ordinary differential equations in the independent generalized coordinates is solved iteratively. The same integration Jacobian is used to determine both the generalized independent accelerations and their sensitivity. All design sensitivity of the dependent variables, including design sensitivity of Lagrange multipliers, are recovered afterwards. Design sensitivity results are verified using finite difference. Efficiency of the proposed algorithm is demonstrated via design sensitivity analysis of HMMWV.

3D3 **Design Sensitivity Analysis and Optimization of High Frequency Problems Using Energy Finite Element Method and Energy Boundary Element Method**

Jun Dong, K. K. Choi, Aimin Wang (U. of Iowa) and Nick Vlahopoulos (U. of Michigan)

A Continuum design sensitivity analysis approach for high frequency NVH problem using sequential Energy Finite Element Analysis (EFEA) and Energy Boundary Element Analysis (EBEA) is developed and presented. The structural energy density and energy intensity is solved by structural EFEA, which is used as the boundary condition of EBEA to compute the far-field energy density and energy intensity. For an adjoint variable method (AVM) in design sensitivity analysis, the adjoint load is obtained from an EBEA re-analysis, and adjoint response is solved from a structural EFEA re-analysis. The sensitivity information of the far-field energy density will only involve the numerical integration on the structural EFEA model. High frequency structural vibration coupled with light and dense fluid are both considered for design sensitivity analysis. Parametric design variables, such as the metal thickness and material hysteresis damping factors are considered for design sensitivity analysis, and numerical results show excellent agreement with the analytical finite difference results. The design sensitivity analysis methodology is integrated into a multi-objective optimization example, in which the Pareto optimum sets are found to minimize both the structural weight and material damping cost, while the structural NVH performance are improved significantly.

3D4 **Design and Optimization of Multi-Material Objects for Enhanced Thermal Behavior**

Yuna Hu (speaker), Vincent Y. Blouin, and Georges M. Fadel, Clemson U.

Multi-material structures take advantage of beneficial properties of different materials in order to achieve increased functionality. A methodology to optimize the multi-material distribution in a given structure, e.g., a brake disk rotor, is presented. The objectives considered in this research are the structural weight and various performance criteria concerning the transient thermal behavior of the object. The optimization combines a transient heat transfer finite element code (FEM) with an evolutionary algorithm library. This approach offers the possibility of finding a global optimum in a discrete design space. This advantage, however, is counter-balanced by high computational expenses due to many FEM evaluations. As a remedy, the optimization procedure is divided into two steps: a global optimization step and a local optimization step. The results of the global optimization step provide an idea of the rough material distribution within the structure and is used to identify regions that have to be further investigated. For the local optimization step the mesh of the identified region is refined and the material model is extended to four material fraction levels. The developed methodology is applied to the optimization of the material distribution in a brake disk rotor.

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Symposium IV

4A Diesel Injection & Combustion

Session Chair: Zoran Filipi

4A1 **Injection System Controls for Promoting Cold Starting and Low White Smoke Emissions**
N. A. Henein, M. Girotra (Wayne State U.), W. Bryzik (TARDEC) and L. Zhong (FEV)
The prompt cold starting of diesel engines depends on the combustion process which can be controlled by the injection system control strategies. The goal of this investigation is to determine the effect of split injection on the cold starting of advanced multi-cylinder diesel engines. Experiments were conducted on a 4-cylinder, high speed, turbocharged, intercooled direct injection engine, equipped with a common rail injection systems. The experiments covered a wide range of split injection strategies and determined their effect on the autoignition and combustion processes, number of cranking cycles and the cycle-resolved hydrocarbons and nitrogen oxides emissions. Also, the effect of the different strategies on white smoke and its constituents is determined. A strategy was developed to produce the minimum number of cranking cycles, gaseous hydrocarbons and white smoke emissions.

4A2 **Investigation of Advanced Injection Strategies for High Power Density and Low Emissions with Computational Fluid Dynamics**
C. Chryssakis, S. Hong, Z. Filipi, D. Assanis, U. of Michigan
In this work advanced fuel injection strategies are explored, in order to reduce harmful pollutant emissions from diesel combustion, while maintaining high levels of power density. Focus is given on simultaneous reduction of NOx and smoke emissions without employing Exhaust Gas Recirculation (EGR). Therefore, the only tool for controlling the combustion and emissions formation processes is by using multiple injections per cycle. Preliminary experimental data indicate that early pilot injections have the potential to reduce both NOx and smoke emissions, compared to single injection strategies, with minimal loss of fuel economy. Furthermore, post injections will be used in order to increase the soot oxidation rate and, thus, reduce the amount of soot in the exhaust gases. The current investigation is based on Computational Fluid Dynamics (CFD) analysis of the in-cylinder processes, namely fuel injection, ignition, combustion and emissions formation. The necessary submodels to model diesel combustion have been selected and implemented into the computational code KIVA-3V. They include the WAVE breakup model for spray breakup, the Shell ignition model, the Characteristic-Time combustion, the Hiroyasu soot formation model and the Zeldovich mechanism for NO formation. In addition, detailed chemical kinetics for ignition and combustion are available, as well as a detailed soot transport model. The models have been calibrated with experimental data acquired from a V-8 International diesel engine, including single and split injection events.

4A3 **Experimental Demonstration of Dual-Use Engine Calibrations: Leveraging Modern Technologies to Meet Military Performance and Emissions Targets**
Jonathan Hagena, Alexander Knafl, U. of Michigan
Modern diesel engines manufactured for production vehicle purposes are calibrated to meet EPA emissions regulations. Many of the technologies incorporated to meet these targets compromise engine performance. When optimal engine performance is required, these emissions-reduction technologies can be used to enhance engine performance and efficiency. A study was conducted on a production medium-duty engine to demonstrate how modifications to its standard calibration can be used to leverage modern technologies to enhance performance. It consisted of operating the engine over an AVL 8-mode test using both the production calibration and an optimized control scheme. It was shown that by properly controlling the engine's EGR and fuel injection systems significant improvements in power, efficiency, and smoke were realized.

4A4 **Visualization and Luminosity Spectral analysis of Diesel Combustion: Effects of Injection Timing, EGR, Swirl and Hydrogen Addition**

Pai-Hsiu Lu, Ming-Chia Lai, Wayne State U.

Low temperature late injection diesel combustion is found to further reduced NOx and soot simultaneously. In addition, hydrogen-rich gas is possible for in-cylinder combustion and after-treatment applications with on-board diesel fuel reformer in the future. This presentation summarizes our recent progress in Visualization and Luminosity Spectral analysis of Diesel Combustion, with particualr emphasis on the Effects of Injection timing, EGR, Swirl and Hydrogen Addition. The combustion phenomena are investigated using high-speed spray/combustion images and time-resolved spectroscopy analysis in a rapid compression machine (RCM) with a small bowl combustion chamber. High swirl and high EGR condition can be achieved in RCM, and high-pressure common-rail fuel injection system supplies variable injection pressure and injection timing. The ignition delay is studied both from the pressure curve and the chemiluminescence images. High-speed color images of spray and combustion show not only the visualization of high-sooting diesel spray impinging on the chamber wall and interacting with very strong swirling air flow, but the color and luminosity of premixed and diffusion flame from combustion chemiluminescence or thermal radiation of soot. Time-resolved spectrum of chemiluminescence from cool flame, premixed combustion, and diffusion flame mainly show the OH radical evolution.

4B Advanced Diesel Engine Systems

Session Chair: Naeim E. Henein

4B1 **Advanced Turbocharging and Power Assist Systems**

Byungchan Lee, Burit Kittirungsi, Andreas Malikopoulos, Zoran Filipi, U. of Michigan

Increased power density of diesel engines is critical for improving mobility and packaging of tactical trucks. In particular, the recent trend of adding armour to light tactical vehicles makes it an imperative to increase power output within the same package size. Achieving high boost pressure allows more fuel-air charge into the cylinders and leads to increased power per unit of engine displacement or mass. The conventional, single stage turbochargers are limited to roughly three bars of boost pressure, hence motivating our work on dual stage turbocharging. The high fidelity engine system with two turbochargers connected in series is modeled in SIMULINK, thus allowing easy evaluation of different configurations and subsequent analysis of in-vehicle transients. Simulation based methodology for matching the two machines for target boost and torque level is presented, leading to a solution for a V6 4.5 L engine. Finally, the Integrated Starter Alternator (ISA) is added to the engine system in order to help with engine transient response, enable electrification of accessories and provide mild hybridization. The performance of the new, high-boost V6 engine combined with a ISA is evaluated in the high-end version of the HMMWV, consequently providing quantitative insight into benefits of potential modernization of this vehicle platform.

4B2 **Effect of Exhaust Gas Recirculation (EGR) in Examining the NOx versus Particulate Matter Emissions Tradeoff in a Heavy Duty Diesel Engine**

Wesley Williamson, Zoran Filipi, U. of Michigan

Analysis of the impacts of flowing EGR from 0 to 20% and injection timing changes on NOx and particulate matter mass emissions on a heavy duty diesel upgraded with a variable geometry turbocharger. Performance in fuel economy and reduction of vehicle emissions smoke signature were considered using a filter smoke meter and low speed data system. High speed in-cylinder data was analysed to verify impacts on in-cylinder combustion analyzed using a high speed data system to conduct apparant heat release studies and determine the effects of EGR and injection timing on combustion.

4B3 **Advanced Thermal Management for High Power Density Diesel Engine**

Hoon Cho, Dohoy Jung, Zoran S. Filipi, and Dennis Assanis, U. of Michigan

The engine cooling system for a high power density diesel engine was modeled with a commercial code, GT-Cool, in order to explore the benefit of electric cooling components on the cooling performance and the fuel economy. As a first step, the conventional cooling system performance was simulated in combination with the high power density engine integrated in the Vehicle and Engine SIMulation (VESIM). As a second step, the mechanical pump sub-model was replaced with an electric pump sub-model and the potential benefit of two different types of electric pumps on fuel economy was investigated with the simulation. Based on the coolant flow analysis a modified thermostat hysteresis was proposed to reduce the electric pump operation, and an additional power saving was achieved with this modified thermostat hysteresis. It was also demonstrated that the radiator size could be reduced without any cooling performance penalty by replacing the mechanical pump with an electric pump.

4C Diesel Engine Modeling

Session Chair: Doug Goering

4C1 **A New Robust Observer for the Accurate Computation of the Instantaneous Total Engine Friction**

Nabil G. Chalhoub, Giscard Kfoury, Naeim Henein (Wayne State U.) and Walter Bryzik (TARDEC)

A reliable algorithm for determining the instantaneous engine friction torque is critical to the research efforts that focus on reducing the fuel consumption and increasing the specific power output of internal combustion engines. The (P-w) method has been introduced, in previous work, as a potential method for predicting the overall engine friction torque. However, its accuracy has been compromised by ignoring the structural deformations of the crank-slider mechanism. Earlier theoretical work has demonstrated that the use of pure rigid body angular velocity and acceleration of the crankshaft in the computation of the friction torque can significantly improve the accuracy of the (P-w) method. This process requires the extraction of the pure rigid body motion of the crankshaft from the measured angular velocity and acceleration signals. Due to the inherent nonlinearities of the crank-slider mechanism, the use of low-pass filters has failed to attenuate the effects of higher order dynamics in the measured signals. Therefore, a robust nonlinear observer, based on the sliding mode methodology, has been developed to predict both the rigid and flexible motions of the crankshaft in the presence of external disturbances and modeling uncertainties. As expected, the use of estimated rigid body angular velocity and acceleration of the crankshaft in the computation of the instantaneous friction torque has dramatically improved the accuracy of the (P-w) method.

4C2 **Lubrication Characteristics of the Bearings of High Power Density Diesel Engines**

Dinu Taraza, Naeim A. Henein, Vadiraj Kulkarni (Wayne State U.), Walter Bryzik (TARDEC)

In high power density diesel engines, the bearings are one of the most vulnerable parts of the engine. They are heavily loaded by forces that are continuously changing their magnitude and direction and maintaining a minimum oil film thickness is critical for the reliability of the engine. The high forces acting in the bearing produce significant deformation of the bearing, complicating the calculation of the minimum oil film thickness (OFT). The paper introduces a fairly rapid method to estimate the minimum OFT, considering the bearing geometry, the bearing deformation and the tilting of the shaft in the bearing. The bearing load is obtained from the polar diagram calculated for the statically undetermined structure of the crankshaft and the position of minimum OFT is determined by the mobility method. The detailed analysis of the lubrication conditions around the position of the minimum OFT is made by calculating the pressure variation at the minimum OFT conditions, based on a finite difference method of integration of the Reynolds equation. This pressure variation is used in a finite element model of the bearing to determine the bearing deformation and the deformations are iterated back in the finite difference grid to recalculate the new pressure variation. The iteration process continues until the pressure variation matches the deformations with a minimum error. The effect of the oil feeding groove and the tilting of the shaft in the bearing are also presented, showing their influence on the bearing loading capacity.

4C3 **Unsteady Convective Heat transfer Modeling and Application to the Intake Manifold of a Spark-Ignition Engine**

Pin Zeng, Zoran Filipi, D. Assanis, U. of Michigan

Unsteadiness is an important feature of the heat transfer in engine manifold. It usually doubles the heat transfer predicted by the steady pipe flow correlation such as the Dittus-Boelter correlation. In order to understand the mechanism how unsteadiness affects the heat transfer, the unsteady heat transfer models are developed from the dimensional analysis of boundary layer momentum equation and the turbulent decay relation. The unsteady heat transfer models indicate that the unsteady heat transfer in the turbulent pipe as well as in the engine manifold consists of two Stages. In Stage I, the heat transfer rate has a phase delay from the velocity variation; the heat transfer coefficient is not only the function of Reynolds and Prandtl numbers but also the function of the velocity changing rate. In Stage II, the heat transfer is controlled by a turbulent decay process. The results of analysis suggest that the phase delay and the turbulent decay controlled heat transfer process in the unsteady flows are all caused by the fact that the turbulent intensity is not in phase with the velocity variation when velocity changes rapidly. A turbulent pipe device was established to validate the newly developed unsteady heat transfer models. The validated unsteady heat transfer models were applied to the heat transfer analysis in the intake manifold of a spark-ignition engine. The prediction of the unsteady heat transfer models agree with the experimental data well.

4C4 **Passive Thermal Management for Future Automotive Systems**

J. M. Ochterbeck (speaker), K. R. Johnson, and P. Rogers, Clemson U.

Designing the thermal management system of these future vehicles will be a difficult task, as the system must reject heat from a number of high power sources (engine, electronics, power conditioning, fuel cells), physically distributed throughout the vehicle. Many traditional thermal paths between generating and dissipating locations will be eliminated when mechanical or electromechanical systems are replaced with electronically controlled systems. The thermal management system should not require auxiliary power for operation. Elimination of auxiliary motors, pumps, fans, and their associated power supplies, has the advantage of reducing vehicle weight and enhances the mobility of military vehicles. Furthermore, a passive system, if properly designed, will be more reliable. Elimination of moving parts, or components requiring maintenance, can only reduce the chance for failure.

4D Vehicle Component Modeling

Session Chair: Dohoy Jung

4D1 **Improved HE-HMMWV Component Models for Powertrain Control**

Doug Goering, U. of Alaska, Fairbanks

Comparison of test data from the XM1124 Hybrid Electric High Mobility Multipurpose Wheeled Vehicle (HE-HMMWV) prototype to simulation models developed at the University of Alaska Fairbanks (UAF) suggests that improvements to the power flow control strategy could result in better fuel economy. In an effort to reduce off-optimum operation of the diesel engine, a sliding mode based robust control algorithm has been developed. The algorithm optimizes power splitting between the engine-generator, battery storage pack, and traction motors and limits operation of the diesel to the optimal torque output range. Implementation of the control algorithm required replacing the map look-up methods, used in the current engine, generator, and traction motor modules, with appropriate analytical models. The new control module has been used to investigate potential performance improvements.

4D2 **Modeling Aspects of Magtrans CVT**

Nilabh Srivastava (speaker) and Dr. Imtiaz Haque, Clemson U.

Continuously variable transmissions (CVT) offer a continuum of gear ratios between high and low extremes. The chief advantage of a CVT is its ability to offer an infinite range of gear ratios with fewer moving parts, and consequently this influences the fuel economy, engine speed, and cost. Although CVTs have lured a great deal of manufacturers and customers, its potential advantages have not been realized completely in a real production vehicle. In order to overcome the torque limitations of the already existing CVTs (belt and chain), Magtrans proposed a new design for CVT. Preliminary models were developed using ADAMS to understand the dynamics of the system and to estimate the torque transmission characteristic of this CVT. Results pertaining to those models and the modeling issues/assumptions pertaining to the CVT will be discussed. Preliminary investigations yield that the system is capable of meeting high load requirements.

4D3 **Mesh Free Reverse Engineering of Automotive Components**

Yohan Fougerolle, U. of Tennessee

Based on R-function theory and on recent supershapes, we introduce a method to represent complex objects as a combination of compact and versatile primitives and its application to automotive components. The resulting object is characterized by an implicit equation, and a technique to compute the solutions is also provided. Additional deformations such as tapering, bending, or twisting can be performed from elementary individual parts to the full object. This approach opens new research directions for reverse engineering by considering any object, even an extremely sophisticated one, as a single equation representing multiple combinations of simpler objects.

4D4 **A Shooting Algorithm for Adjoint Sensitivity Equations**

Andrei Schaffer, Dale Holtz, U. of Iowa

Backward stability of multibody system index-3 adjoint Differential- Algebraic Equations (DAE) is analyzed. A boundary value problem (BVP) formulation is presented for the coordinate partitioning underlying ordinary differential equations (CPUODE) of the adjoint DAE. A shooting algorithm is proposed for solving the backward homogeneous adjoint CPUODE BVP with terminal conditions only. Gradients of functionals used for optimization and design sensitivity analysis of a multibody system are computed using linearly independent solutions of the homogeneous adjoint CPUODE. The functionals' gradients are incrementally updated forward in time. Therefore, the need to store the equations of motion generalized coordinate vector, and possible its time derivatives, and start the backward integration of the adjoint DAE after the integration of equations of motion is done, is eliminated. In addition, linearly independent solutions of the homogeneous adjoint CPUODE are computed in parallel.

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