

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 11-12-2013		2. REPORT TYPE Final Addendum to the Final Report		3. DATES COVERED (From - To) 09/19/2013-11/18/ 2013	
4. TITLE AND SUBTITLE Integration of Computational Geometry, Finite Element, and Multibody System Algorithms for the Development of New Computational Methodology for High-Fidelity Vehicle Systems Modeling and Simulation				5a. CONTRACT NUMBER W56HZV13C0032	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Ahmed A. Shabana				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Computational Dynamics Inc. 1809 Wisconsin Ave Berwyn, IL 60402				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Army Tank-automotive Research Development & Engineering Center, Warren, Michigan 48397-5000				10. SPONSOR/MONITOR'S ACRONYM(S) TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Report developed under SBIR contract for topic A12-069. This project aims at addressing and remedying the serious limitations of the three-decade old multibody system (MBS) software technology currently used in the analysis, design, virtual prototyping, and performance evaluation of modern vehicle systems. These limitations are well known and are documented in the literature. The analysis of modern vehicle systems requires the development of complex models that include significant details that cannot be captured or accurately simulated using existing MBS codes which are based on rigid body assumptions or small deformation finite element (FE) formulations that are not suited for efficient communications with CAD systems. It is the main objective of phase I and Phase I Option of this SBIR project to demonstrate the feasibility of developing a new MBS software technology that is based on new concepts and algorithms that can be used for accurate and efficient simulation of military and civilian wheeled and tracked vehicle models that include significant details. The progress made in Phase I and Phase I Option has been documented in several reports and has been communicated with TARDEC. The results obtained are also documented in several technical reports and refereed journal paper.					
15. SUBJECT TERMS Multibody systems, finite elements, computational geometry, vehicle dynamics.					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON Dr. Paramsothy Jayakumar
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) (586) 282-4896

Name of Contractor Computational Dynamics Inc. (CDI) 1809 Wisconsin Avenue Berwyn, IL 60402	Contract Number W56HZV-13-C-0032
Report Date November 12, 2013	Period Covered by the Report September 19, 2013 – November 18, 2013
Project Title Integration of Computational Geometry, Finite Element, and Multibody System Algorithms for the Development of New Computational Methodology for High-Fidelity Vehicle Systems Modeling and Simulation	Security Classification Unclassified
CDI Principal Investigator (PI) Ahmed A. Shabana	Name of Issuing Government Activity DOD Small Business Innovative Research (SBIR) Program Program Solicitation FY 2012.1, Topic A12- 069
Report Type Final Addendum to the Final Report	Sponsoring Agency U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) 6501 E. 11 Mile Rd. Warren, MI 48397-5000
Project Description Feasibility Study	Sponsoring Agency Technical Representative Dr. Paramsothy Jayakumar TARDEC

Project Summary

This project aims at addressing and remedying the serious limitations of the three-decade old multibody system (MBS) software technology currently used in the analysis, design, virtual prototyping, and performance evaluation of modern vehicle systems. These limitations are well known and are documented in the literature. The analysis of modern vehicle systems requires the development of complex models that include significant details that cannot be captured or accurately simulated using existing MBS codes which are based on rigid body assumptions or small deformation finite element (FE) formulations that are not suited for efficient communications with CAD systems. It is the main objective of phase I and Phase I Option of this SBIR project to demonstrate the feasibility of developing a new MBS software technology that is based on new concepts and algorithms that can be used for accurate and efficient simulation of military and civilian wheeled and tracked vehicle models that include significant details. The new software technology will allow for: 1) preserving CAD geometry when FE analysis meshes are created; 2) modeling large deformation in MBS applications; 3) implementation of general constitutive models; 4) development of new efficient FE/MBS meshes that have constant inertia and linear connectivity conditions; and 5) use of numerical integration procedures that satisfy the constraint equations at the position, velocity, and acceleration levels; these integration methods will not require the numerical differentiation of the forces, and will take advantage of the sparse matrix structure of the MBS dynamic equations. A successful integration of CAD computational geometry (CG), nonlinear large displacement FE, and flexible MBS algorithms is necessary for the development of the new software technology. Such an efficient integration can be accomplished using the nonlinear FE absolute nodal coordinate formulation (ANCF) that allows for preserving CAD geometry, implementing general material models, using general large deformation continuum mechanics approach, developing new FE meshes that have constant inertia matrix and linear connectivity conditions, and exploiting the sparse matrix structure of the MBS dynamic equations. Implicit and explicit numerical integration procedures that ensure that the constraint equations are satisfied at the position, velocity, and acceleration levels will be used in order to avoid violations of the basic mechanics principles.

Project Objectives

The objectives of this project as stated in the proposal of Phase I and Phase I Option are summarized as follows:

1. **Integration of CG/FE/MBS Algorithms** The feasibility of integrating CG/FE/MBS algorithms using ANCF finite elements will be demonstrated in Phase I of this project. The limitations of using the isogeometric approach in MBS analysis will also be explained.

2. **Large Deformations and Material Models** The feasibility of developing general large deformation algorithms that have new features and can be the basis for the development of the new software technology will be demonstrated in this SBIR project.
3. **New Kinematic and Inertia Description** The feasibility of developing and using the FE meshes that have constant inertia and linear connectivity conditions and their implementation in a general MBS algorithm that can be used as the basis for developing the new software technology will be demonstrated in Phase I and Phase I Option of this project.
4. **New Numerical Solution Procedure** The principal investigator (PI) recently proposed an implicit sparse matrix integration procedure, called TLSMNI (Two-Loop Sparse Matrix Numerical Integration) that ensures that the kinematic constraint equations are satisfied at all levels, exploits the sparse matrix structure of the constrained dynamic equations, and avoids the numerical differentiation of the forces. The use of this new procedure will be examined and the feasibility of its implementation will be demonstrated in this SBIR project.

The objectives of this project have not been changed.

Progress Made During the Reporting Period

The progress made during this reporting period can be summarized as follows:

1. **Flexible Body and Contact Modeling:** UIC and CDI continued to work on the improvement of the flexible body and contact modeling implementation in order to demonstrate the feasibility of developing a new efficient software technology for the nonlinear dynamic analysis of complex MBS applications. It was recognized that 15% of the rigid tracked vehicle simulation time is devoted to the periodic change of the set of dependent coordinates. The change of degrees of freedom is necessary in order to avoid the possibility of having singular or ill conditioned constraint Jacobian matrix, a situation which may lead to inaccurate results or failure of the simulation. When non-sparse techniques based on the Gaussian elimination is used to determine the independent coordinates, a full pivoting procedure is used to select an appropriate set of coordinates. This process can be very expensive due to the large number of constraints and coordinates. The use of a new sparse matrix implementation that exploits the sparsity of the constraint Jacobian matrix when identifying the independent variables was explored. The preliminary studies conducted indicate that the new sparse matrix implementation can be very efficient compared to the full matrix pivoting and saves almost 15% of the simulation time. Efforts are currently being made to generalize the new technique and to find the best set of parameters to be used.

UIC and CDI also continued to optimize the flexible tracked vehicle contact subroutines and the implementation of the new ANCF meshes that have constant inertia and linear connectivity conditions. These new developments are being documented in a paper which is being finalized. A draft of this paper was sent to TARDEC and when finalized the paper will be sent for journal publication.

Studies conducted at UIC also demonstrated that ANCF finite elements can be effectively used for developing an efficient total Lagrangian approach for modeling fluid

dynamics [1]. For the most part, fluid dynamics problems are solved in the literature using an Eulerian approach. ANCF fully parameterized solid elements ensure the continuity of the displacement gradients and have no restrictions on the amount of deformation within the element, and therefore, these elements can be used to efficiently solve fluid problems as demonstrated in a report recently published. Implementation of the new ANCF fluid elements in the new software technology will be necessary in order to be able to solve practical problems in which accurate modeling of fluid sloshing is necessary. This new total Lagrangian approach for fluid modeling will allow for the successful integration of FE computational fluid dynamics and multibody system algorithms.

2. **Soil Mechanics Model Implementation:** In order to demonstrate the feasibility of the implementation of the soil model, a MATLAB code was developed. This code was used to demonstrate that the Cam-Clay model leads to the results expected. Efforts have continued since the last report to establish a robust implementation of the Cam-Clay materials and also the simpler Drucker-Prager soil model. The nonlinear equation solver used in the models was found to be very sensitive to the scale of the simulated material. A more appropriate formulation for the nonlinear equation solver was implemented to help increase the robustness of the material model. Investigations with linear material models are being used to help reveal any other issues and potential problems. As previously reported, a number of model configurations have been constructed to test the response of the recently implemented ANCF solid element. A considerable amount of work was expended to verify the response of the solid element for various configurations. It was found, as previously reported, that the element is working appropriately for simulations including linear elastic and plastic material models under small and large deformations with uniform meshes. The implemented nonlinear hyperelastic law was tested against an analytical solution for uniaxial loading conditions and found to be in agreement with infinitesimal predictions under uniaxial loading conditions. The investigation of the Fortran implementation of the infinitesimal Cam-Clay model continued in order to determine possible sources of error in both application and implementation. With a verified infinitesimal model, work can quickly proceed towards verification of the finite deformation Cam-Clay model. The models will need to be verified against published data before conclusive results may be presented.

After publishing the comprehensive soil mechanics paper in the 2013 July issue of the *ASME Journal of Applied Mechanics Reviews* [2], which explains the procedure for the implementation of the ANCF soil model in MBS algorithms, CDI, UIC, and TARDEC continued to work on a second paper that will demonstrate the implementation of ANCF continuum soil models in MBS algorithms. A draft of this paper will be sent to TARDEC once it is completed.

3. **Development of M113 Vehicle Model:** As recommended by TARDEC, work on developing different M113 tracked vehicle models continued. Simulations have been successfully accomplished for the rigid body tracked vehicle using different configurations. The tracked vehicle model has been simulated in a half-round impact event with the specifications given in a TARDEC/CDI/UIC teleconference to match the estimated 2.5*g of acceleration felt on the chassis. Details and results will be presented

for both rigid and flexible tracked models. Further work is being implemented toward post-processing for the stress analysis of a rigid track link.

The paper on the joint formulation has been finalized and was published in the journal of *Nonlinear Dynamics* [3]. As previously reported, this paper presents a study that compares different formulations for the track link joints, including the ideal joint, penalty method, bushing element, and continuum based ANCF joints. It is the goal to develop a preprocessor that will allow the development of new ANCF joints and will eliminate the dependent joint variables before the dynamic simulation starts. This will allow for significantly reducing the number of dynamic equations and Lagrange multipliers. In existing MBS algorithms, the joint constraints are implemented in the main processor. The nonlinear algebraic equations that define these joints must be satisfied at the position, velocity, and acceleration levels. Eliminating these algebraic equations at a preprocessing stage will significantly reduce the number of equations and number of nonzero entries. Further development of this pre-processing capability will allow for using a concept similar to the concept of the knot multiplicity used in computational geometry methods (B-spline and NURBS), and will allow developing new models for soil and tires by imposing higher degree of continuity on higher order elements. This will lead to efficient computer models that have much smaller number of degrees of freedom.

4. **Preparation for Phase II Project** Preliminary planning for Phase II project with specific tasks to be completed every 2 months was submitted to TARDEC. CDI is in a position to start working on these tasks immediately once the Phase II contract is signed.
5. **Tel-Conferences, Communications, and Meetings:** During this reporting period, there were several E-mail communications with TARDEC. One tel-conference was held on November 7, 2013. During this tel-conference, presentations were made by Ulysses Contreras, and Michael Wallin. Prior to this tel-conference, another tel-conference that included Caterpillar was held on September 9, 2013 in order to discuss the soil modeling.

REFERENCES

1. Wei, C., and Shabana, A.A., "A Total Lagrangian Finite Element Formulation for Fluid Dynamics Problems", Technical Report # MBS2013-5-UIC, Department of Mechanical Engineering, The University of Illinois at Chicago, October 2013.
2. Contreras, U., Li, G.B., Foster, C.D., Shabana, A.A., Jayakumar, P., and Letherwood, M., "Soil Models and Vehicle System Dynamics", *Applied Mechanics Reviews*, Vol. 65(4), 2013, doi:10.1115/1.4024759.
3. Wallin, M., Aboubakr, A.K., Jayakumar, P., Letherwood, M.D., Gorsich, D.J., Hamed, A., and Shabana, A.A., "A Comparative Study of Joint Formulations: Application to Multibody System Tracked Vehicles", *Nonlinear Dynamics*, Vol. 74(3), 2013, pp. 783-800.