MULTI-SCALE IN TIME PROJECTILE-TARGET HPC SIMULATIONS FOR LETHALITY AND SURVIVABILITY

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ABSTRACT

The Objective Force concept requires technology advantage over the adversaries to design, develop, model and simulate weapon systems that are strategically responsive, deployable, agile, versatile, lethal and survivable. As the Army transforms there is a renewed interest in the concept designs of new projectile-target weapons systems. As the modular systems are developed, optimized and ultimately integrated to the continuously evolving FCS, there is a critical need for a "next-generation" sate-of-the-art computer modeling and simulation tools. In addition, there is also critical need for have a single, validated, maintainable high performance computing (HPC) code which captures the physics of short and term dynamic events to drastically reduce simulation times. In this paper, we present a new and advanced HPC based multi-scale in time projectile-target simulation environment for lethality and survivability that is useful for FCS design concepts. Illustrative examples are considered that demonstrate the capabilities of the proposed approach.

1. INTRODUCTION

Strategically agile and responsiveness of Armored vehicles depends on the sensitive electronic components. A structural design that eliminates potential failure of these sensitive electronic components is influenced by the shock wave propagating through the structure due to impact loads and is highly critical. Numerous efforts during the past several years have focused on accurate modeling and predicting the force-time histories of local events such as contact, impact, penetration, and penetration induced damage due to projectiles to accurately predict the global structure response of the target. See for example, work by Saliba et. al, 1996 and references there in.

In lieu of this, there is a renewed interest in the Army for the next generation of projectile-target interaction software technology that can accurately predict the global structure response of the target due to local events with drastic reduction in the simulation times. These simulations in general are a multi-scale in time physics where events are occurring with respect to different time

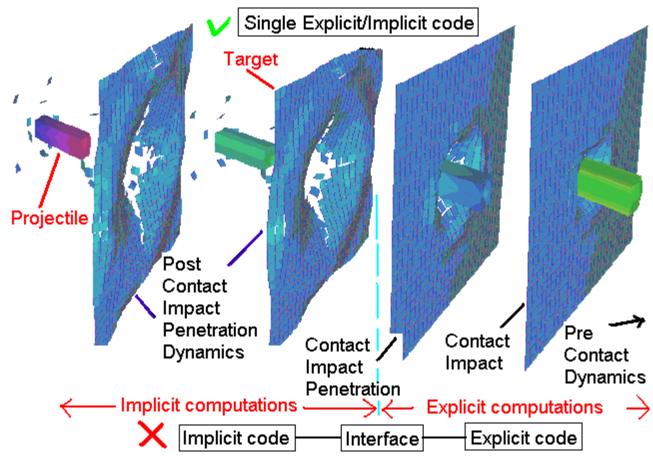


Figure 1. Illustration of the multi-scale in time events in a projectile-target interaction system. A unified scalable validated HPC based multi-scale in time software is highly desirable to account for proper data transfer of physics from explicit to implicit and implicit to explicit phases of the computations.

scales. For example, the events occurring at small time scales (micro time scales), namely, are the short-term localized penetration/impacts of projectiles into the targets. Similarly events occurring at larger time scales (tenths of a second or even longer) are the global dynamic response such as structural vibrations of the targets. When subjected to short-term contact-impact-penetration followed by the post dynamics of the long-term contact-impact effects they are inherently all coupled in the problem definition. For example, low frequency and long-term dynamics are dominant from the initiation of flight dynamic conditions till contact is made and subsequently after the weapon leaves the target. Similarly, high frequency and short-term dynamics are dominant during the contact-impact-penetration stage. These sequences of events are described in Fig. 1. Therefore, there is also critical need for have a single, validated, maintainable high performance computing (HPC) code which captures the physics of short and term dynamic events to drastically reduce simulation times. In addition, there is wide range of applications in which distinct regimes of explicit and implicit computations can be identified. To cite a few readers are referred to Finn et al. 1995 and Narkeeran and Lovell, 1996.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 DEC 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Multi-Scale In Time Projectile-Target Hpc Simulations For Lethality And Survivability**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Mechanical Engineering, University of Minnesota Army High Performance Computing Research Center, Minneapolis, MN 55455**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

For these multi-scales in time physics simulations, most of the researchers are relying on a standalone explicit computational technology such as that in PARADYN (Hoover et al., 1994), EPIC (Johnson, et al., 1997), etc., for the entire transient analysis. In these intensive computation-based simulations, the conditional stability associated with the Linear Multi Step based explicit time integration technique such as the central difference method severely limits the total simulation duration to be completed in a reasonably practical amount of time. More specifically, the post dynamics of contact-impact dynamic simulation is unbearable and is very expensive when employing these standalone explicit computations. Alternatively, the implicit computational techniques that are employed in ABAQUS, 2004; NIKE3D, 1995, etc., are not suitable in the high velocity impact simulations regime since it cannot capture the stress wave propagation at larger time step sizes. Alternatively, during the post dynamics simulation regime, the parallel implicit computations are not scalable because of lack of a scalable solver technology that is required to effectively solve implicit system of equations at each time step and during the nonlinear iterations phase.

We have developed and herein present a HPC based multi-scale in time physics software based on: 1) novel computational algorithms with a smart switch which adaptively decide explicit and semi-explicit strategies, 2) robust contact-impact algorithms describing the physics of contact via linear complementary formulations for normal direction and augmented Lagrangian formulation in tangential direction, and 3) large strain finite deformation mechanics with a new arbitrary reference configuration methodology.

The research efforts are focused on delivering this HPC based end product for the Army initiatives and to successfully demonstrate the effectiveness to the Objective force. The benefits of this HPC software technology are many folds. They are: 1) reduced run times of an order of magnitude for problems involving contact-impact and long-term post dynamics as against employing standalone explicit computation based codes, 2) a unified code instead of a combination of codes for avoiding erroneous approximations introduced in combining different codes and for ease of maintainability, and 3) better parallel scalability which implies effective utilization of the Army HPC resources. All these technological advances and the potential impact are demonstrated in this paper.

2. FORMULATION

The projectile-target interaction involves a multitude and multiple physics such as the rigid body motion, the structural vibrations, the contact/impact events, the damage and fracture process including non-linear material and large deformation. In this section, the governing equations of these aspects are briefly described.

Momentum equation: The weakform of the momentum equation can be stated as

$$(\boldsymbol{w}, \frac{\partial(\rho \boldsymbol{v})}{\partial t} + \rho\eta \boldsymbol{v})_{\Omega_t} + (\boldsymbol{D}(\boldsymbol{w}), \sigma)_{\Omega_t}$$
$$= (\boldsymbol{w}, \boldsymbol{b})_{\Omega_t} + (\boldsymbol{w}, \boldsymbol{f})_{\Gamma_f(t)} + (\delta \boldsymbol{g}, \sigma_n + \sigma_\tau)_{\Gamma_c(t)}$$

where $\boldsymbol{w}$ is the virtual displacement field, $\boldsymbol{v}$ is the velocity field, ρ is the density, η is the viscous damping, $\boldsymbol{D}$ is the virtual velocity strain, σ is the Cauchy stress, $\boldsymbol{b}$ is the body force, $\boldsymbol{f}$ is the external force, $\boldsymbol{g}$ is the gap vector function, σ_n is the normal contact force, σ_τ is the frictional force, $\delta\boldsymbol{g}$ is the virtual gap, Ω_t is the material domain, $\Gamma_f(t)$ is the Neumann boundary, $\Gamma_c(t)$ is the contact boundary, and (•,•) represents the inner product.

Contact constraints - Impenetrability conditions: The weakform associated with contact constraints that lead to complementary conditions can be stated as

$$(\tau_n, g_n - \lambda_n^c \boldsymbol{n})_{\Gamma_c(t)} = 0$$
$$\lambda_n^c \geq 0$$
$$\psi_n(\sigma_n) = \sigma \cdot \boldsymbol{n} \geq 0$$
$$\lambda_n^c \psi_n(\sigma_n) = 0$$

where τ_n is the virtual normal contact force, g_n is the normal direction gap vector, λ^c_n is the Lagrangian multiplier represents the normal contact force, and $\boldsymbol{n}$ is the normal contact direction.

Frictional boundary condition: Similarly, the weakform associated with frictional force at the contact surface can be stated as

$$(\tau_\tau, \dot{g}_\tau - \lambda_\tau^c \nabla_{\sigma_\tau} \psi_\tau(\sigma_\tau))_{\Gamma_c(t)} = 0$$
$$\psi_\tau(\sigma_\tau) \geq 0$$
$$\lambda_\tau^c \geq 0$$
$$\lambda_\tau^c \psi_\tau(\sigma_\tau) = 0$$

where τ_τ is the tangential virtual frictional force, g_τ is the tangential direction gap vector, λ^c_τ is the Lagrangian multiplier represents the frictional force, and $\psi_\tau(\sigma_\tau)$ is the friction law.

Constitutive Equation: The hypoelastic constitutive equation are considered which can be written in the form

$$\tilde{\sigma} = (1 - D_d)^{-1} : \sigma = \sigma : (1 - D_d)^{-1}$$

$$\tilde{\sigma}^{\nabla} = C : (D - \dot{\gamma} \frac{\partial F(\sigma; D_d, Y)}{\partial \sigma})$$

where $\tilde{\sigma}$ is the effective-Cauchy-stress, D_d is the damage tensor, $\tilde{\sigma}^{\nabla}$ is the objective effective-Cauchy-stress, $\dot{\gamma}$ is the Lagrangian multiplier represents the plastic and damage flow magnitude, $F(\sigma; D_d, Y)$ is the plastic and damage dissipative potential function, and Y is the energy release function due to damage.

3. ADAPTIVE SMART SWITCH ALGORITHM

An adaptive algorithm based on a smart switch formulation was developed, implemented, and tested for various applications involving contact-impact events. This algorithm switches between the explicit computations and semi-implicit computations based on the detection of the physical event. For explicit computations, a forward displacement central difference (FDCD) algorithm (Sha et al., 1996) was employed and for the semi-implicit computations a nonlinearly explicit and L-stable (EL) algorithm (Zhou et al., 2004) was employed. The physical events can be rigid-body in-flight motion of the projectile, low/high velocity impact, penetration and damage, and post-impact structural dynamic vibrations. This formulation is particularly useful if these physical events are in a sequence as the time step size employed during one phase of computations to another is global in nature.

The physical events that are associated with the projectile-target interaction can be classified based upon the following four parameters. They are the acceleration of the nodes, gap function between the colliding bodies, damage stress, and the damage state. Then, if **I** is the event function which detects these events, it can be stated as:

$$I \Leftarrow (I_0, I_1, I_2, I_3, I_4) \Leftarrow (a_{norm}, g_{min}, \sigma_d, \omega_{crit}) \quad (1)$$

where I represents the physical events, a_{max} is supremum of the acceleration vector, **a**, g_{min} is the infimum of the gap vector, **g**, σ_d is the damage stress threshold value, and ω_{crit} is the critical damage state. The evaluation criteria to determine the specific physical events is described next.

3.1 In-Flight Motion

In-flight motion predominantly consists of rigid body motion. For the rigid body motion, we assume the system is subject to no external force, thus the supremum of the acceleration is zero. And, also the collision between the bodies has not yet taken place, which is characterized by the gap distance between the projectile and the target to be greater than a given critical value, g_{crit}. Therefore, we have

$$I = I_0 \Leftarrow \{a_{max} = \sup |\mathbf{a}| = 0\} \cup \{g_{min} = \inf|\mathbf{g}| > g_{crit}\} \quad (2)$$

For rigid body motion (except the rigid rotation), no physical models and time integration is needed, and the system can simply update the displacement by multiplying the velocity by the time step size.

3.2 Contact/Impact

When the minimum distance between the projectile and the target is smaller than the given critical value, and the maximum second invariant of the stress is less than the material damage stress threshold value, we consider the contact/impact events are taking place in the system. This condition can be stated as follows.

$$I = I_1 \Leftarrow \{a_{max} > 0\} \cup \{g_{min} < g_{crit}\} \cup \{\sigma_2 < \sigma_d\} \quad (3)$$

During this contact/impact stage, the code adaptively switches to explicit computations for solving equations pertaining to structural dynamics, finite deformation and contact constraints.

3.3 Damage

When the minimum distance between the projectile and the target is less than the given critical value and the maximum second invariant of the stress is greater than the damage stress threshold value but the scalar damage parameter is less than the critical damage state, we consider the system is undergoing the damage stage. This state is given by,

$$I = I_2 \Leftarrow \{a_{max} > 0\} \cup \{g_{min} < g_{crit}\} \cup \{\sigma_2 > \sigma_d\} \cup \{\omega < \omega_{crit}\} \quad (4)$$

In this stage, the code still employs explicit computations in solving equations pertaining to structural dynamics, finite deformation, contact constraints, and the damage mechanics.

3.4 Penetration

When the minimum distance between the projectile and the target is less than the given critical value, the maximum second invariant of the stress is greater than the material damage stress threshold value but the scalar damage parameter is greater than the critical damage state, we consider the system is undergoing the penetration stage. This is given by,

$I=I_3 \Leftarrow \{a_{max}>0\}\cup\{g_{min}<g_{crit}\}\cup\{\sigma_2>\sigma_d\}\cup\{\omega>\omega_{crit}\}$ (5)

In the penetration stage, the code still employs explicit computations in solving equations pertaining to structural dynamics, finite deformation, contact constraints, and damage mechanics with erosion.

3.5 Post-Impact/Penetration Dynamics

When the supremum of the acceleration is not equal to zero, but the minimum distance between the projectile, the target, and the debris due to the penetration is greater than the given critical value, we consider the system is undergoing post-impact/penetration dynamics stage. This is given by,

$I=I_4 \Leftarrow \{a_{max}>0\}\cup\{g_{min}>g_{crit}\}$ (6)

In the post-impact/penetration dynamics, the computations adaptively switch to semi-implicit computations with a larger time step size for the solution of equations pertaining to structural dynamics and finite deformation.

In summary, the projectile-target interaction involves multiple physical events and some of the physical events are low-frequency dominated (long time scale) and some of the physical events are high-frequency dominated (short time scale). The design of the current smart switch adaptive algorithm is based on the assumption that these physical events associated with the projectile-target interaction occur sequentially wherein during each stage of the physical event we employ the appropriate physical models and time integration methods to handle the specific physical events. Efforts are currently underway to adaptively handle multiple physical events based on element based computations with smart switch where some elements solely explicit while some elements are solely semi-implicit in the same finite element mesh.

4. PARALLEL FORMULATIONS

The increasing complexity of this emerging and next generation survivability–lethality technology needs higher fidelity in numerical models to capture the geometry and material behavior under realistic operational loading scenarios, for large scale geometries such as an entire army vehicle to be included in these simulations (see Fig. 4). This is unlike existing approaches where only a representative section of the vehicle is mostly considered (for example a plate section) for the simulation in survivability–lethality designs. Increasing model fidelity requires high mesh resolutions. Longer simulation times are needed to assess post dynamic simulations after contact, impact, penetration, and damage events. Computational requirements grow dramatically as the size and complexity of the computational models increase. As the element size is decreased to capture the finer details such as in large deformations in geometry and for overall response, the time step also decreases to satisfy the stability criteria in explicit time integration during the small time scale simulation regime. This reduction in the time step results in the need for long CPU times to complete a simulation. Scalable parallel computations and development and implementation of new computational methods and HPC algorithms which solely do not reliy on explicit features but fusion of explicit/semit-implicit technologies are the primary focus and an important component of the multi-scale in time computational technology. Developments that are platform independent and can be ported to different HPC architectures, we use message-passing interface (MPI).

An efficient parallel finite element procedure for contact-impact computations within the framework of multi-scale in time physics is needed. The scalability of this depends on the following key kernels: i) parallel mesh generation, ii) parallel mesh partitioning, iii) parallel motion integration and solvers, iv) parallel global contact search, and v) parallel contact interface solver (linear complementary equations). The parallel mesh generation is not considered in this research. The kernels such as parallel motion integration and solvers that are typical of transient non-linear finite element computations are omitted in this in paper. The reader is referred to Kanapady and Tamma, 2003, for more details for paralleization aspects pertaining to this kernel. In this paper attention is restricted to parallel mesh partitioning, parallel contact search and the parallel contact interface solver.

4.1 Mesh Partitioning

The first stage of parallization involves partitioning of the finite element mesh into sub-domains as shown in Fig. 3 and 5. Each sub-domain is then mapped on to a processor with the objective of balancing the computational loads and minimizing the communications between all the processors. Mesh partitioning considering only the finite element force calculation may lead to unstructured communication during global contact search as contact segments may be owned only by few processors. In addition, where the contact is going to take place is not known a-priori and also this keeps changing during the simulation, and hence load imbalances may occur. Two different partitioning stages can be considered: one with finite elements as the computational load and the second with the contact segments as the computational load. This however requires extra communication at every time step of the computations between the finite-element decomposition and contact decomposition. Multi-constraint graph partitioning for simultaneous data partitioning for finite-element force calculation and contact search can be employed thereby eliminating extra communication at every time step. To over come these situations a multi-constraint graph-partitioning library proved in ParMetis (Karypis and Kumar, 2002) is employed. This provides the requested load balanced partition for both the elements and contact segments partitions simultaneously. The numerical experiments on various large-scale finite element meshes have shown that the partitioning time is reduced by 30% to 40% in comparison to two separate partitioning operations. In addition, this partitioning approach provides well-balanced partitions for both finite elements and contact segments.

4.2 Parallel contact search

Solving for the contact force by employing the linear complementary approach in conjunction with the node-to-segments approach requires defining the gap function constraints and their corresponding Jacobians. The node-to-segment approach requires the contact segment and a node pair list which satisfies the minimum gap criteria. This process of finding contact segment node pairs list involves an all-to-all $O(n)$ contact segments search leading to $O(n^2)$ time. This can dramatically increase the time needed for the whole simulation. To reduce cost, contact searches is usually performed in two stages. In the first stage, called global search, the pairs of contact segment and node that are potentially be in contact are determined. In the second stage, called local search, the exact contact segment and node pairs are detected from the reduced number of pairs list of the global search stage. Once the global search is paralliezed then the local search phase can be performed independently by each of the processors. In this paper we only focus on the global search phase, as it is critical for ensuring the overall parallel scalability of the simulation.

Zhong and Nilsson, 1989 have proposed a sequential global contact-searching algorithm with contact hierarchies known as hierarchy-territory algorithm, or HITA. In the HITA algorithm, a contact system is defined which consists of contact surfaces, contact segments, contact edges, and contact nodes. These are arranged in a hierarchy to form a tree. Territories in terms of bounding box are defined for each of the contact objects in the hierarchies that define the domain they occupy during the contact process during the simulation. If the territories of two contact objects in certain hierarchy level intersect then contact search is performed between the contact objects at the lower level else no contact search is performed between the lower levels. In our initial parallelization efforts, we have parallelized this algorithm and implemented in Contact-Impact-Analysis (pCIA-3D) code. The input this parallel global contact search routine includes: i) is the entire contact surface information, ii) co-ordinates and velocities at the current time step, iii) time step size and iv) the number of time step for which the global contact search is valid. The output the library consists of the following. The contact segment and node pair list in the processor in which contact segment resides. The node information consists of the processor or sub-domain to which it belongs, node co-ordinates and the velocities. From this point onwards each processors can perform the local contact search.

4.3 Parallel contact interface solver

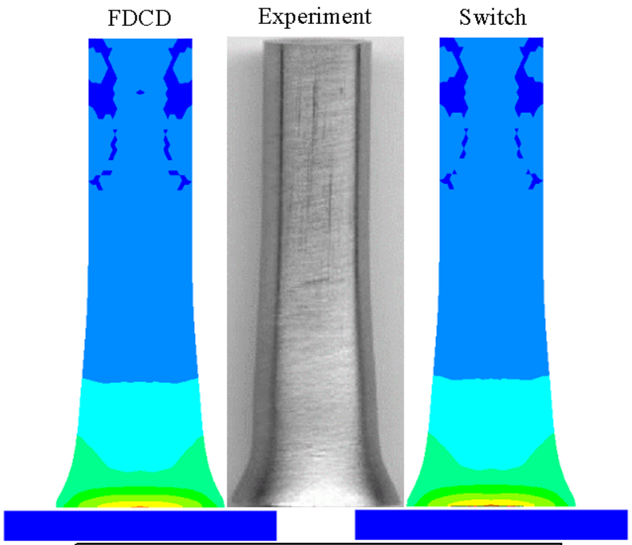
Once the contact segment-node pairs are found, the normal and the tangential force at the actual contact surface between various contacting bodies needs to be solved. For this purpose, we employ conjugate projected gradient solver developed in Sha et. al 1996 is employed. The parallel implementation of this solver involves local matrix-vector operation and vector operations. In addition, there are nearest neighbor communications and two collective communications. Since, predominantly for most time of the simulation actual contact surface owned by number of processors are few compared to the number of processors employed in the simulation, the communication overhead is small especially for the collective communication. Thus, parallel overhead associated with parallel contact interface solver kernel is very small ensuring overall parallel scalability of the simulation.

5. RESULTS

In this section, illustrative examples are considered that validate and demonstrate the capabilities of the proposed approaches. In particular, the computational CPU time savings by employing multi-scale in time approaches for large-scale computations such as an entire Army vehicle simulation and the parallel performance results are presented. The simulated results are compared with experimental results for validation purpose for simple cases.

An adaptive algorithm based on a smart switch formulation was developed, implemented, and tested for various applications involving contact-impact events.

First, the standard Taylor bar impact problem was considered to compare the explicit only computations and the smart switch based explicit/semi-implicit computation with experimental results available in the literature (Hanson and Hemez, 2002). The bar impacting a rigid plate at 245.7 m/sec was considered. The initial length to final length of the bar and initial radius to the final radius of the bar at the impacting surface of the simulation results to experimental results are compared. A finite element mesh consisting of 83k tetrahedral elements is



Experiment (Hanson & Hemez, 2002), $L^*/L_0 = 0.838$, $R^*/R_0 = 1.581$		
	FDCD	Switch
L^*/L_0	0.824 (-2.0%)	0.824 (-2.0%)
R^*/R_0	1.629 (+3.0%)	1.629 (+3.0%)
Average error	2.5%	2.5%
e_p^{max}	1.585	1.589
CPU (ratio)	1	3.98

Figure 2: Taylor bar impact problem with/without switch algorithm showing plastic strain, and final deformed shape of the bar in comparison with experimental results.

considered. The Fig. 2 shows the simulated results in comparison with the experimental results. The following observations are evident from the results. First, from the plastic strain contour plots, the explicit only computations results are similar to the results of explicit/semi-implicit computations with a smart switch. The final deformed shape is in close agreement to the experimental results with an error of 2% on the length and an error of 3% on the radius. A computational speedup of 3.98 (CPU timings are normalized) is observed with the smart switch based computations.

In the second example, some relevant to the parallel performance results, we will consider again the Taylor bar impact problem. A finite element mesh consisting of 250k elements is considered. Figure 3 demonstrates the parallel speed-up for the same.

The third example consists of ten spherical balls impacting a plate. This example is considered to demonstrate the CPU advantage of the smart switch based explicit/semi-implicit computations when multiple impacts are involved in a random sequence. The Fig 4 shows the stress contour plots of the sequence of contact-impact events occurring when these balls are impacting

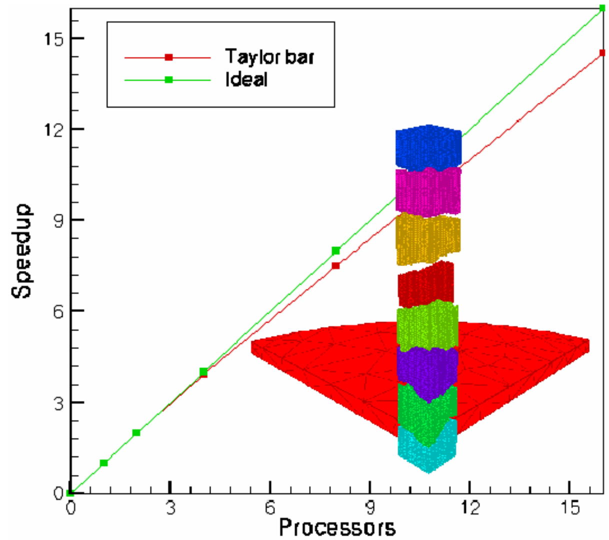


Figure 3: Initial parallel performance results for contact-impact problem - Taylor bar impact problem.

on the deformable plate. The bar chart demonstrates that CPU advantage of switch based computations of 3.5 times over the explicit only computations.

Finally, example demonstrates the large-scale computational capabilities of the software pCIA-3D. The application of this technology to the initial FCS design concepts is illustrated in Fig 5. The Fig 5a shows the entire Army vehicle modeled with 1.27 million tetrahedral elements impacted with several projectiles at different rates and different times to simulate multiple short-scale local events and subsequently the long-scale events such as vehicle body vibrations. The goal here is to demonstrate the prediction of the global response including structural vibration and wave propagation in the structure for local contact and impact events. The Fig. 5b shows the finite element mesh partitioned into 64 partitions. The Fig. 5c shows the typical stress contour in the structure for a typical instant of time. The simulation analysis shows an order of magnitude of saving in run times (see Fig 5d) as compared to the standalone explicit-based computations.

6. CONCLUSIONS

In this paper, we present a new and advanced HPC based multi-scale in time projectile-target simulation environment for lethality and survivability that is useful for FCS design concepts. Illustrative examples were considered that demonstrate the capabilities of the proposed approach to include: 1) reduced run times of an order of magnitude for problems involving contact-impact and long-term post dynamics as against employing

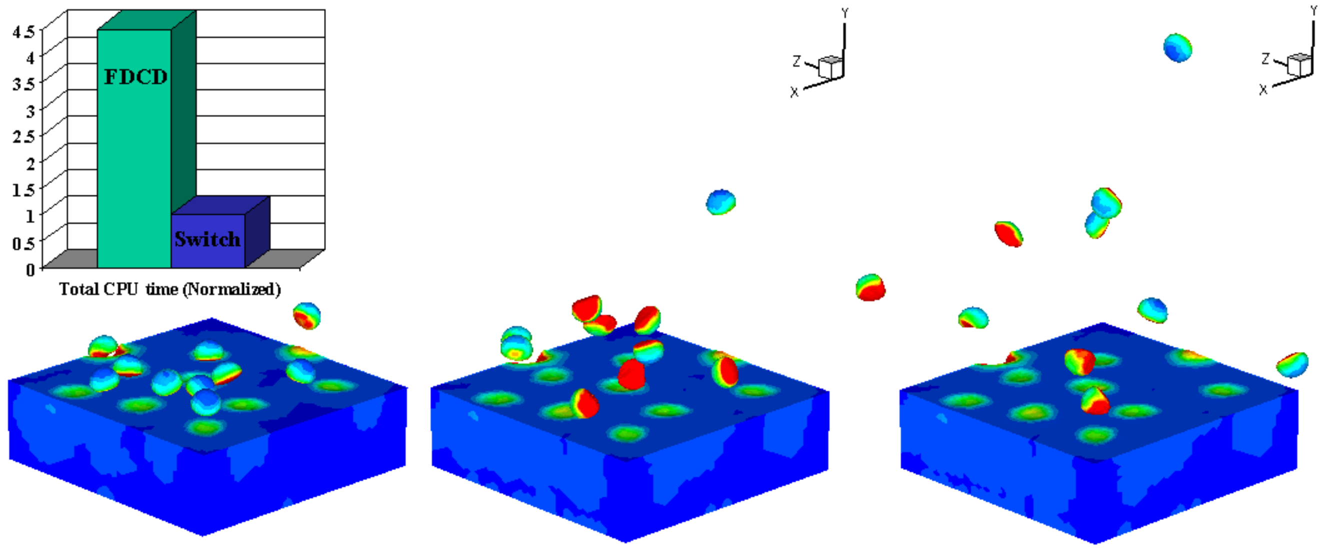


Figure 4. Sequence of contact-impact simulation of ten spheres colliding with each other and a deformable plate. The bar char illustrates the speedup of the simulation of 3.5 times of switching based simulation to only explicit based computations.

standalone explicit computation based codes, 2) a unified code instead of a combination of codes for avoiding erroneous approximations introduced in combining different codes and for ease of maintainability especially in the context of employing HPC, and 3) better parallel scalability which implies effective utilization of the Army HPC resources.

ACKNOWLEDGMENTS

The authors are very pleased to acknowledge support in part by Battelle/U.S. Army Research Office (ARO) Research Triangle Park, North Carolina, under grant number DAAH04-96-C-0086, and by the Army High Performance Computing Research Center (AHPCRC) under the auspices of the Department of the Army, Army Research Laboratory (ARL) under contract number DAAD19-01-2-0014. The content does not necessarily reflect the position or the policy of the government or the policy of the government, and no official endorsement should be inferred.

REFERENCES

ABAQUS, 2004, www.abaqus.com

Attaway S. W., 1990: Update of PRONTO2D and PRONTO3D Transient Solid Dynamics Program, SAND90-0102, Sandia National Laboratories, Albuquerque, New Mexico, 1990.

Finn, M, Pgalbraith, P.,Wu, L., Hallquist, J., Lum, L., and Lin, T.L., 1995: Use of a coupled explicit-implicit solver for calculating spring-back in automotive body panels, J. of Material Processing Technology, **50**, 395-409.

Hanson, K. M. and Hemez, F. M., 2002: Bayesian Calibration of Simulation Models Using Experimental Data. In Proceeding of NECDC 2002, California, October 21—24.

Hoover, C. G., DeGroot, A. J., Maltby, J. D., and Procassini, R. J., 1994: PARADYN — DYNA3D for massively parallel computers. Engineering Research, Development and Technology FY94, LLNL, UCRL 53868-94.

Johnson, G. R., Stryk, R A., Holmquist, T. J., and Beissel S. R., 1997: User instructions for the 1997 version of the EPIC code. Wright Laboratory, Armament Directorate, Eglin Air Force Base report, WL-TR-1997-7037.

Kanapady, R. and Tamma, K. K., 2003: *A-Scalability* of an Integrated Computational Technology and Framework for Non-linear Structural Dynamics - Part II: Implementation Aspects and Parallel Performance Results, Int. J. Numer. Methods Engrg., **57**. 2295-2323.

Karypis, G., Schloegel, K., and Kumar. V., 2002: PARMETIS 3.0: Parallel graph partitioning and sparse matrix ordering library. Technical report, Department of Computer Science, University of Minnesota.

Laursen, T. A. and Simo, J. C., 1991: On the formulation and Numerical Treatment of Finite Deformation Frictional Contact Problems, in Nonlinear Computational Mechanics – State of the Art, P. Wriggers and W. Wanger, eds. Springer-Verlag, Berlin, 716—736.

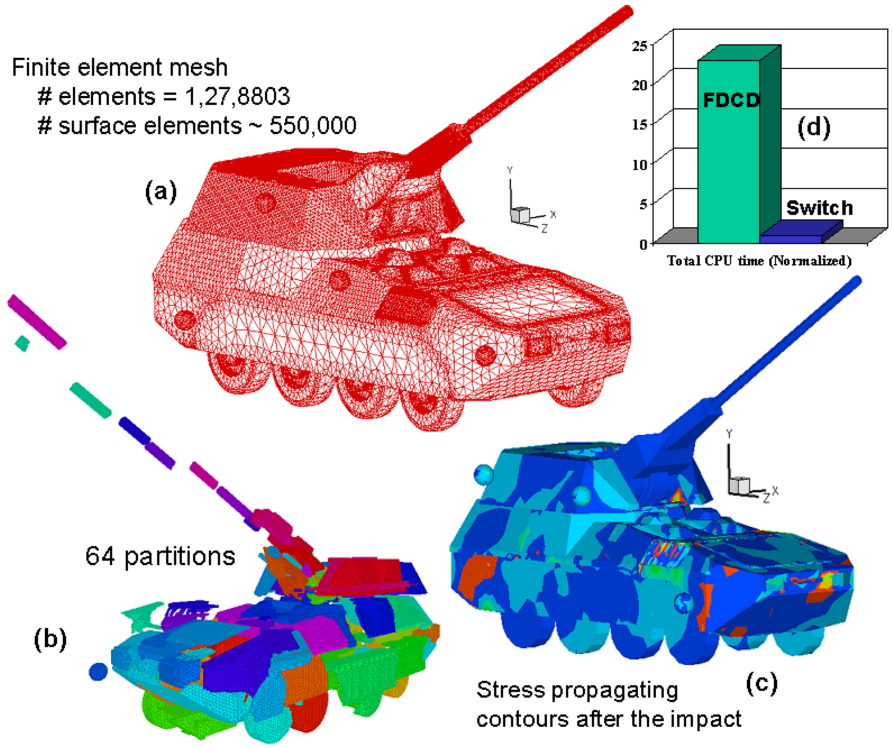


Figure 5: The global response of the structure for local events such as contact and impact. Initial FCS design with entire Army vehicle modeled with 1.27 million finite elements impacted with several projectiles at different rates and different times to simulate multiple short-scale local events.

Narkeeran, N. and Lovell, M., 1999: Predicting Spring-Back in Sheet Metal Forming: an Explicit to Implicit Sequential Solution Procedure, Finite Element in Analysis and Design, **33**, 29-42.

NIKE3D, 1995: A Nonlinear, Implicit, Three-Dimensional Finite Element Code For Solid And Structural Mechanics, User's Manual, UCRL-MA-105268 Revision 1.0.

Saliba, J. E., Dhar, S., Grove, D. J., and Brar, N. S., 1996: Prediction of Force-Time Histories in Thick Steel Plates Due to Penetration by Tungsten Rods at Velocities of 1.5-2.5 kn s^{-1}, Int. J. Solids Structures, **33**(10), 1453-1477.

Sha, D., Tamma, KK. and Li, M., 1996: Robust Explicit Computational Developments and Solution Strategies for Impact Problems Involving Friction, Int. J. Numer. Methods Engrg., **39**, 721-739.

Zhong, Z-H, and Nilsson. L., 1989: A Contact Searching Algorithm, for general contact problems,, Computers & Structures, **33**, 197—209.

Zhou, X., Sha, D. and Tamma, K. K., 2004: A Novel Nonlinearly Explicit Second-order Accurate L-Stable Methodology for Finite Deformation Hyperelastic/Hypoelasto-plastic Structural Dynamics Problems, Int. J. Numer. Methods Engrg. **59**, 795-823.