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Warfighter/Hardware in the Loop Simulation at TACOM-TARDEC's Ground Vehicle Simulation Laboratory (GVSL)

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Warfighter/Hardware in the Loop Simulation at TACOM-TARDEC's Ground Vehicle Simulation Laboratory (GVSL)

Patrick Nunez, Mark Brudnak, and Victor Paul of the TACOM-TARDEC GVSL

ABSTRACT

The National Automotive Center (NAC) Ground Vehicle Simulation Laboratory (GVSL) is developing and applying engineering simulators and simulations for the evaluation of ground vehicles during all stages of a weapon system's life cycle - research, development, and procurement of new systems; technology insertion and modifications to fielded systems; and trouble-shooting activities arising from test and field related incidents.

The GVSL employs integrated laboratory experiments and mathematical modeling and analysis capabilities in the areas of structural integrity and durability, vehicle ride and stability, gun/turret control algorithms/hardware, and human-centered, total system performance studies. Recent upgrades to the GVSL real-time component, the Warfighter/Hardware in the Loop Simulation Laboratory (WHLS Lab), have motivated GVSL engineers and scientist to investigate and develop or apply simulation technologies that facilitate the evaluation of weapon systems in the context of an integrated man-machine system prior to the physical existence of hardware components or fully integrated physical systems.

GVSL BACKGROUND

The GVSL develops and applies engineering simulations and simulators in support of the United States Army's military ground vehicle research, development, acquisition and life cycle management missions. The GVSL is capable of measuring, predicting and evaluating typical automotive performance characteristics such as vehicle ride and shock dynamics, handling, stability, durability, and human performance factors.

The real-time component of the GVSL, the WHLS Lab, may be configured to incorporate new simulation technologies, models of new vehicle technologies or conceptual designs, and crew compartment hardware. These components are integrated into the GVSL WHLS Lab to create an integrated virtual system that may be evaluated at the component level, system level (including the warfighter), small unit level (using multiple processors to provide a small number of ground vehicles working together), and force level (large numbers of manned vehicles and Computer Generated Forces (CGF) interacting over a network in a single virtual battlespace).

History

(TACOM's history described in the next two paragraphs is condensed from reference (1)).

The GVSL is located at the Tank-automotive and Armaments Command (TACOM) Tank-Automotive Research, Development and Engineering Center (TARDEC) in Warren, Michigan. TACOM has its roots in the establishment of the Detroit Arsenal (located in Warren Township) in 1941. The Detroit Arsenal was created to produce tanks for an Allied armored force to combat the growing presence of German armor in Europe. In 1942, the Tank-Automotive Center was established in Detroit to manage Army wheeled and tracked vehicle systems. The Tank-Automotive Center was renamed the Office, Chief of Ordnance-Detroit (OCO-D) before the end of World War II and was dismantled at the end of the war. During the Korean War, the Army created the Ordnance Tank-Automotive Center (OTAC) in order to handle nationwide procurement of all ground vehicles.

As the cold war developed and both NATO and Warsaw Pact forces planned for large armored battles, the Tank-Automotive Command (TACOM) was officially established in 1967 and was given the responsibility for managing all Army ground vehicles. In 1995, TACOM added the US Army's Armament and Chemical Acquisition and Logistics Activity (ACALA) in Rock Island, Illinois and the US Army Armament Research Development and Engineering Center (ARDEC) in Picatinny, New Jersey. TACOM was then renamed the Tank-automotive and Armaments Command, retaining the TACOM acronym. Finally, in 1998, TACOM added the Anniston Army Depot in Alabama and the Red River Army Depot in Texas to its organization. Today, TACOM is spread over five states and, with it's Logistic Area Representatives (LAR), eighty-one countries. It's facilities include over 1.2 million square feet of research and development facilities and laboratories and over eleven thousand civilians and soldiers – twenty-five percent in the state of Michigan.

Since the 1940s, TACOM has been a significant contributor to the scientific investigation of ground vehicle performance including the areas of off-road mobility, human vibration tolerance and multibody dynamics modeling – core areas of the GVSL today. A fundamental tenet employed by TACOM engineers in gaining insight into many problems has been to combine physical laboratory experimentation with analytical tools and techniques.

M. G. Bekker 's work at OCO-D in off-road ground vehicle mobility during the 1940s (2) resulted in equations relating vehicle tractive performance to both soil and vehicle properties. Bekker's terramechanics model continues to be the basis for most physics-based modeling of intrinsic vehicular off-road mobility.

The NATO Reference Mobility Model (NRMM), an empirical model used by the US Army in evaluating off-road mobility, was developed primarily through the efforts of TACOM and the Corps of Engineers' Waterways Experiment Station (WES), located in Vicksburg, Mississippi.

TACOM has also had significant involvement in the area of off-road vibrations of ground vehicle and the effects on the human operator. Theoretical investigations by Pradko and Lee (3,4) at TACOM in the 1960s defined the concept of absorbed power and, through experimental studies, demonstrated that a strong correlation exists between the measurable, objective quantity of absorbed power and the subjective feel of ride quality. The concept of absorbed power is used in defining the ride quality of Army vehicle systems. Lins (5) measured human vibration response and developed transfer functions describing human vibration response that are used in developing absorbed power values.

In the late 1970s, the GVSL funded work by the University of Iowa towards developing a general purpose, constrained, multibody dynamics methodology, which eventually became the commercial software package "Dynamics Analysis and Design System" (DADS), now available from LMS-CADSI. The GVSL contributed significantly to the initial development of DADS and continues to develop modified versions of the software in-house for the performance of a fundamental GVSL capability – vehicle dynamics analysis and predictive simulation.

Basic research into real-time vehicle dynamics in the late 1980s and the 1990s by Wehage, Belczynski, Gunter, Letherwood, and Lamb created a multibody dynamics methodology called the Symbolically Optimized Vehicle Analysis System (SOVAS)(6,7). SOVAS achieves efficient run-time performance through the use of a reduced set of state variables and precomputed tables of closed-loop kinematics and precomputed velocity cross-coupling factors. SOVAS has proven to be an efficient and reliable modeling methodology for real-time simulation system development within the WHLS Lab (8).

Today's GVSL is a high-tech integrated laboratory that continues the TACOM tradition of combined physical experimentation and theoretical analysis. With the addition of collocated DoD High Performance Computing and networking facilities, the level of integration between laboratory and analysis has grown significantly and today's GVSL is able to drive high-performance motion platforms using fairly complex constrained multibody vehicle models traversing high-resolution, off-road terrain.

GVSL Core Capability: Obtain/Analyze Design Data, Performance Data, Human Factors Data

Motion simulators, analytical computer modeling, predictive simulation, and high performance computing are integrated within the GVSL in order to provide a wide spectrum of ground vehicle analysis capabilities. Motion simulators subject vehicle systems (both real and virtual), components, and occupants to a variety of dynamic environments that emulate typical proving ground tests or field operations. Three dimensional computer models of ground platform systems are used in predictive simulations in order to assess vehicle ride, handling, stability, and structural integrity. The Department of Defense High Performance Computing Modernization Program provides state of the art computational horsepower and engineering software packages for vehicle modeling, simulation, and analysis and to generate motion and synthetic environments for operator in the loop simulations in the GVSL WHLS Lab.

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Physical laboratory assets of the GVSL include two durability simulators, two six Degree of Freedom (DOF) man-rated simulators, and an inertial measurement rig. The durability simulators - the Reconfigurable N-Post Simulator (RNPS) (Figure 1) and the Pintle Motion Based Simulator (PMBS) - are used for laboratory durability experiments and to characterize vehicle systems (9). The high performance Ride Motion Simulator (RMS) and the high capacity Crew Station/Turret Motion Based Simulator (CS/TMBS) were built to perform warfighter/hardware-in-the-loop simulation experiments. The Vehicle Inertial Properties Evaluation Rig (VIPER) is used to measure mass, inertia and static load design data. The VIPER is capable of measuring center of gravity positions (±1%), moments of inertia (±3%), and weight and axle loads (±1 lb.) for vehicles or components between fifteen hundred pounds and thirty tons and sizes up to one hundred and twenty inches in width and four hundred and thirty-one inches in length.

FIGURE 1 HMMWV Characterization Using the RNPS

Analytical skills and tools in the areas of multibody dynamics and finite element analysis are employed by the GVSL to evaluate the dynamic (Figure 2) and structural (Figure 3) performance of ground vehicles. The GVSL commonly studies vehicle ride and shock dynamics, steering and handling performance, structural integrity, and dynamic stability (during typical vehicle mobility operations and as a weapon-firing platform). The analytical work of the GVSL scientists and engineers is used to predict the behavior of ground platforms and in integrated analytical-physical experiments to provide load history inputs to drive the durability and engineering simulators. Letherwood and Gunter (10) describe how the GVSL uses analytical computer modeling and simulation in evaluating vehicle design and performance, along with describing a step by step process of how the virtual prototyping process is used by the GVSL.

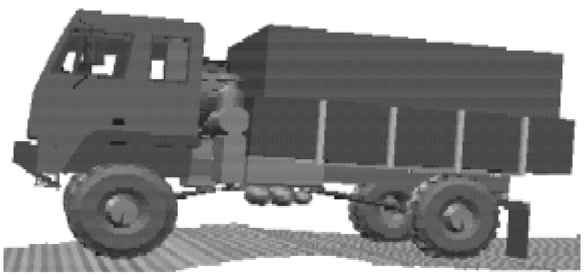

FIGURE 2 Military Truck Dynamic Analysis A model of a Military Truck is used to recreate dynamic loading conditions leading to driveshaft failures .

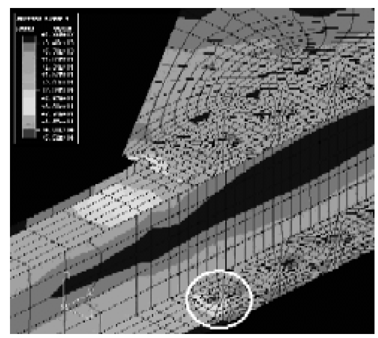

FIGURE 3 Trailer Structural Analysis
The GVSL provided combined physical durability simulation, finite element analysis and vehicle dynamics analysis into an investigation of the cause of structural failures of a trailer during testing.

GVSL WHLS LAB

The warfighter-centered capabilities of the GVSL focus on creating a virtual environment within which a vehicle model may be operated by a warfighter and the total system performance evaluated. Many components are integrated to present a warfighter with a realistic operating environment. It is the behavior of the total system – including the warfighter - during realistic mission profiles that the GVSL WHLS Lab is interested in capturing. The remainder of this paper concentrates on simulation technologies required to perform experiments to evaluate total system performance from this perspective. The RMS and CS/TMBS motion platforms present the dynamic motion environment to the warfighter. Advanced computing and networking hardware are used to tie the motion platforms to the image generators, real-time infrastructure and vehicle dynamics software.

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Motion Base Simulators

At the heart of the GVSL WHLS Lab are the Crew Station/Turret Motion Base Simulator (CS/TMBS) and Ride Motion Simulator (RMS) (Figures (4) and (5)). Each are designed to reproduce the harsh vehicle motions of military ground vehicles traversing secondary and cross-country terrains.

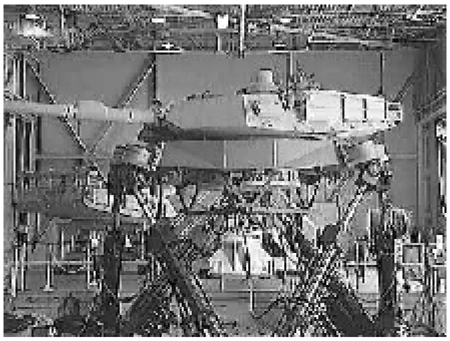

FIGURE 4 : Crew Station/Turret Motion Base Simulator (CS/TMBS)

The CS/TMBS, one of the largest simulators of its kind, is a high capacity, six degree-of-freedom (6- DOF) hexapod capable of accommodating both reconfigurable vehicle crew stations or fully active combat vehicle turret systems of up to 25 tons. The simulator allows for vehicle occupants to "ride" in the motion base and operate the crew station or turret system hardware while under motion. It offers remarkable repeatability and control over variables difficult to manage at proving grounds, thus producing high quality data and valid test results. Applications include gun/turret drive characterization, control system algorithm development, turret structure development, crew station and soldier/machine interface development. Specifically, the simulator has been used to perform a variety of "baseline vs. modified" studies on vehicle gun/turret drive and weapon stabilization systems and subsystems such as the Bradley M2A2/M2A3 turret traverse drive motor (11).

The RMS is the second of the GVSL's 6-DOF simulators. It is a high-performance, single occupant motion base designed to recreate the "ride" of nearly any ground vehicle with high precision and accuracy. The simulator has two vehicle cabs that are essentially space frames that allow for a variety of vehicle configurations. The simulator was specifically designed for crew station and human-in-the-loop experiments. The RMS has a much higher bandwidth than most traditional driving simulators enabling it to recreate the high-frequency vibration often found in military vehicles traversing rough, cross-country terrains. The RMS has been safety certified by both the TACOM and Army Developmental Test Command Safety Offices and is man-rated for operator-in-the-loop experiments. It has been used in the characterization of warfighter body/seat dynamics for different vehicle systems. Technical specifications on both simulators are shown in Table 1. In addition, both simulators offer the ability to present high-resolution visual and audio cues to the simulator occupants.

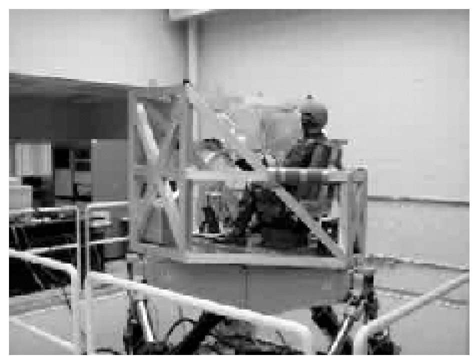

FIGURE 5 : Ride Motion Simulator (RMS)

Table 1 GVSL Engineering Simulator Specifications

	RMS	**CS/TMBS**
Translational Motion *(vert, lat, long)*		
Displacement	±20 in	±30 in
Velocity	±50 in/s	±70 in/s
Acceleration *(Max ind. transient)*	±2 g	±4 g
Bandwidth (Hz) *(3 dB Frequency)*	40	10
Rotational Motion *(roll, pitch, yaw)*		
Displacement	±20 deg	±20 deg
Velocity	±70 deg/s	±70 deg/s
Acceleration	±1150 deg/s^2	±1700 deg/s^2
Max Payload	1600 lbs	25 Tons

Both the RMS and CS/TMBS share common motion controller designs. The simulators may be operated in either world position or world acceleration control. In either control mode, the six motion commands (longitudinal, lateral, and vertical translations, and roll, pitch, and yaw rotations) can be input to the controller from: a data file containing the output of analytical simulations; scaled analog voltages from instrumented physical testing; or via ScramNet reflective memory network. In the latter, the motion base controllers receive their position/acceleration commands from a real-time vehicle dynamics model running on other computing assets. When conducting operator-in-the-loop driving simulation, it is essential to present the occupant with the most realistic environment possible in order to avoid unnatural and undesired occupant responses. This can be achieved by presenting tightly correlated visual, auditory and motion cueing. For the latter, it is important for the motion base to present all of the motion cues that are within the bounds of human perception. These are primarily the vehicle's translational accelerations and rotational velocities (12). The GVSL simulators, like many other 6-DOF motion bases, are limited by their motion envelope in recreating the low-frequency motion cues necessary for the most realistic simulation environment. Because of this, classical washout filters are implemented in the motion controllers to mitigate the affects of these limitations. They work on the principle that a constant, sustained acceleration (i.e. low frequency) is indistinguishable from a gravitational field. The washout algorithms are constructed to directly apply higher frequency motions ("transients") and use "slow" motion platform rotations to utilize the Earth's gravitational field to impart perceived low frequency accelerations. In addition, the washout algorithms use limiting, filtering and scaling to "fit" the desired motion within the motion envelope of the simulator.

High Performance Computing and Networking

The GVSL has been the beneficiary of a Department of Defense (DoD) effort to maintain its high performance computing capabilities. The GVSL is collocated with the TACOM-TARDEC DoD High Performance Computing Distributed Center (HPCDC) (Figure 6). In 1997, TACOM-TARDEC was designated a High Performance Computing Distributed Center (HPCDC) in order to support the real-time warfighter-in-the-loop simulation efforts and fulfill the requirement of the GVSL for multiprocessor, multi-platform capabilities without large networking latency.

HPCDC assets include an SGI Onyx2 Reality Monster (with thirty-two R12000 processors and thirty-two GB of memory) and an SGI Origin 2000 (with four MIPS R12000 processors and one GB of memory) that is used exclusively by the GVSL for real-time system development and testing. The Onyx2 Reality Monster is used for many applications including WHLS Lab simulations, GVSL dynamic and finite element analyses, and scientific visualization within TARDEC. For visualization applications, the Onyx2 is equipped with four Infinite Reality 2 graphics pipes and a Lightwave Graphics Network that allows for high speed transport of up to 10,000 feet without a significant degradation in video signal. The Lightwave network is used to connect the HPCDC graphic capabilities located at the GVSL facilities with visualization centers in other TARDEC buildings.

FIGURE 6 : TACOM-TARDEC High Performance Computing Center

While the HPCDC provides the scalable architecture for large-scale simulations and for model development and testing, the real-time environment also uses a Concurrent TurboHawk (with eight PowerPC 604e processors) system. The TurboHawk's deterministic real-time architecture is used for all of the time critical process scheduling. It is the "conductor" of the real-time simulation.

Since the real-time simulation components execute on distributed computer assets, a mechanism for communication between these assets is necessary. All of the computers are inter-networked via 100Base/T Ethernet communications. This is sufficient for event-based communications, however, Ethernet does not meet the timing and determinism requirements necessary for the transmission of high-rate continuous data required by a real-time dynamic simulation. For this purpose the GVSL uses ScramNet reflective memory. ScramNet provides one hundred and fifty megabits per second transmission rate over fiber-optic media. It guarantees a bounded transmission time (in the microseconds), and provides a means by which to transmit interrupts. The GVSL uses a ScramNet ring to communicate all continuous data that crosses process boundaries. It is used as an interface for controlling the Evans and Sutherland Image Generators (IG). It provides vehicle state information to the motion controllers (RMS and CS/TMBS) for the washout algorithms and the rendering of vehicle motion. It also serves as a means of distributing a low-rate clock to all of the necessary subsystems.

Image Generation

In warfighter-in-the-loop simulations, it is necessary for the subject to have a view into a virtual world that is as realistic as possible. The GVSL uses advanced Image Generators (IG) and display systems from Evans and Sutherland (E&S) to provide visual stimulus to the operator. The IGs used are the E&S Image Generator 3000 High Definition (ESIG 3000 HD) and the E&S Harmony. The RMS display system consists of either a set of reconfigurable flat-panel displays, which can be arranged to simulate from one to three vision blocks; or, a set of three large displays for the purpose of rendering the wide field-of-view that is necessary for most wheeled vehicles. The display system available for the TMBS is a 360° ring of ten large angle displays intended for mounting on an M1A2 Abrams, M2A2/3 Bradley, or a Light Armored Vehicle (LAV) turret. This display system is intended to naturally excite panoramic vision blocks which are attached to the subject turret. An additional display is used to excite the gunner's primary site, if necessary.

The ESIG 3000 HD is capable of rendering 3 channels of video, with three rasterized displays each. This has been the primary IG used by the WHLS Lab in developing the human-centered simulator system. The WHLS Lab is in the process of integrating the Harmony IG, which represents the next generation of image generation technology from Evans and Sutherland. The Harmony offers the capability of Phong shading and bump map texturing which allow the rendering of complex surfaces, such as terrain and textures, without increasing the polygon load. Phong shading uses information in the texture map on a polygon to define a unit normal vector for each pixel. The Phong algorithm together with the bump map textures use these vectors to define how light is reflected from the surface, and yields a convincing impression that a two dimensional polygon extends in to the third dimension. By using these advanced displays and the Harmony IG, the GVSL hopes to convince the test subject, to the extent possible with today's technology, that they are in a real environment; hence, the subject will respond as if they were in a real physical system.

Real-time Vehicle Dynamics

Real-time models of the ground vehicle systems are used by the GVSL WHLS Lab to provide motion signals to the simulator platform. Steering wheel angle, throttle and brake position, gear selector position, or other mission-specific operator controls are captured from the RMS or CS/TMBS crew cab. Ground profiles and soil information are queried from a terrain elevation database that is correlated with the visual terrain presented on the operator displays. The vehicle dynamics model calculates the response to operator inputs and the terrain profile and soil characteristics. The vehicle response is fed into the washout algorithms which filter the accelerations and provide the motion path to the simulator platform – high frequency motion is applied directly and low frequency motion is indirectly created by motion platform rotations. In order to avoid a loss of simulator fidelity and induced simulator sickness (both of which result in undesirable experimental results), the vehicle models must be capable of operating in hard real-time (deterministic temporal behavior) while retaining numerical accuracy and stability. With operator safety paramount in a man-rated system, the ground vehicle model must remain stable through the entire range of possible operation, or it must catch unstable conditions and gracefully recover.

The strict requirement imposed by the real-time operation makes it difficult to include a large degree of detail in a vehicle model. If component level analyses are required, the model must contain sufficient detail to include the components being investigated; or the real-time simulation should be considered inappropriate for that particular application. On the other hand, if the simulation behavior of interest is limited to system level vehicle behavior, then the model could be developed with a lower level of detail, but built with the direct purpose of predicting the system level response.

The GVSL WHLS Lab is using both constrained multibody dynamics formulations and system level vehicle dynamics formulations. The constrained multibody codes consist of the in-house developed Symbolically Optimized Vehicle Analysis System (SOVAS) and the National Advanced Driving Simulator & Simulation Center (NADS-SC) developed High Performance Dynamics Code (HPDC). The system level codes are System Technologies, Incorporated's (STI) Vehicle Dynamics Analysis Nonlinear (VDANL) and a variant of the CARSIM package from Mechanical Simulation Corporation (MSC).

SOVAS, the result of in-house basic research into real-time vehicle multibody dynamics, has proven to be a very stable and reliable basis for real-time vehicle modeling. It does not have a complete suite of development tools and is largely unpolished as a usable package. The WHLS Lab is investigating the possibility of transferring the SOVAS technology into the commercial sector through the use of a Cooperative Research And Development Agreement (CRADA) with Realtime Technologies, Inc, a commercial partner that has provided significant assistance in developing the GVSL WHLS Lab. This may allow the SOVAS method, which shows promise as a real-time multibody dynamics methodology, to be wrapped up in a user-friendly interface with model development tools that could be used by the WHLS Lab and made commercially available.

SOVAS shortcomings in the areas of usability and completeness caused the WHLS Lab to initiate a contract in 1998 to develop a more usable real-time, multibody dynamics package. The result is the High Performance Dynamics Code (HPDC), developed by NADS-SC at the University of Iowa. HPDC brings a set of graphical model development tools to WHLS Lab real-time vehicle modelers. Model development is facilitated through the use of the commercial multibody dynamics package DADS as the front-end for basic vehicle chassis and suspension and a Java-based interface for engine, drivetrain, brakes, steering, tire and track, and aerodynamics subsystems. HPDC has three components that the WHLS Lab uses. The fundamental capability of real-time model execution (a linkable library compiled into the WHLS Lab simulation software) is used for vehicle models driving the motion platforms. A complete model analysis and debugging set of tools is available as HPDCLab. Lastly, a stand-alone static simulation environment is used to interactively drive vehicle models for demonstration and debugging purposes.

While the multibody dynamics codes of SOVAS and HPDC form the core of the real-time vehicle dynamics capabilities of the WHLS Lab, the restrictions imposed by real time performance requirements significantly effect the level of detail that may be included within HPDC. SOVAS, though not as sensitive as HPDC to the number of bodies in a model (due to the use of precomputed tables for closed loop kinematics and precomputed factors used in the equations of motion (13)), is difficult to use. If the specific locations of individual bodies are not of interest in a particular experiment, such as is the case if we simply want to providing accurate translational acceleration and rotational velocities to a driver, the advantages of a system level vehicle dynamics package become significant. System level dynamic codes do not typically require the iterative solutions of a multibody code. As such, they are easily adapted to operate in a real-time environment. This fact - along with the idea that more detail in a vehicle model does not always imply improved accuracy - indicate that, in certain applications, the use of system level dynamics code is preferable to constrained multibody methods.

The WHLS Lab and STI, under a phase II Small Business Innovative Research (SBIR) contract, are developing a system level, real-time, ground vehicle simulation package based upon the commercial STI offering, VDANL, with some additions for off-road applications and a suite of standard virtual military truck and combat vehicle tests. This assures real-time activity for any vehicle model developed that fits into the system level description that VDANL is developed around. The disadvantage of a system level package like VDANL or CARSIM is the loss of flexibility in model topology and the loss of visibility into component behavior and interaction. However, the strict timing requirements of real-time performance significantly limit the amount of detail that can be included in a constrained multibody model, somewhat diminishing the advantages of the constrained multibody methods. The WHLS Lab, at this time, is continuing to pursue both methods.

Real-time Infrastructure

The GVSL WHLS Lab consists of a set of hardware with each individual component selected for its exceptional performance. The use of high-end hardware for each aspect of the simulation necessarily decentralizes the hardware into a collection of disconnected subsystems. Given this decentralized set of hardware, it became necessary to develop, or preferably, acquire a means by which to consolidate these individual pieces of hardware into a cohesive whole. 100Base/T Ethernet and SCRAMNet provide the media and the low level protocol for communications. An architectural framework that could coordinate the communications between hardware systems and software modules was needed. Upon surveying the community, it became apparent that no one product had emerged as the defacto standard for implementing such a framework. In fact many laboratories used their own homegrown framework to meet similar needs. After considering a couple of alternatives, the GVSL WHLS Lab chose the C Object Oriented Programming System (COOPS) from MTS Systems Corporation.

COOPS is an object-oriented software system which was designed by MTS to run hard-real-time motion controllers. It has many desirable features, such as clocking and scheduling tools, an object-orientated representation for all software, a means for passing continuous sampled data across process boundaries, synchronous and asynchronous TCP/IP communications, distributed object representation, and is entirely written in ANSI C, largely machine independent. Given all of these capabilities, the GVSL WHLS Lab added SCRAMNet communications and interrupt handling to this list of capabilities. Using COOPS, an architecture was designed to implement all of the necessary functions as classes in COOPS. Each class specification in COOPS includes a list of its instance variables, a set of methods which implements the services to be provided by an instance of the class, and a set of continuous data terminals by which an object receives continuous inputs and transmits continuous outputs. If an object is to be periodically executed (as most are), then the class provides one method which is executed once every time its timing source is triggered. The clock is an instance of a separate class that encapsulates platform specific implementations.

The method chosen does have some drawbacks. It does not have a GUI interface. There is one module in the COOPS software that is heavily platform/compiler dependent. COOPS does not have an established customer base to formalize its updates and provide support. Currently there still does not exist that defacto standard which is necessary to implement such architecture.

CURRENT GVSL WHLS LAB ACTIVITIES

The current capability of the WHLS Lab consists of interactive operation of several ground vehicle entities over virtual representations of several off-road databases. The ground vehicle model library currently consists of a Infantry Fighting Vehicle (M2), a Main Battle Tank (M1), a HMMWV, and a generic Truck. The off-road terrain library includes the Ft. Irwin P2 area from the National Training Center, and parts of Churchville, Munson, Perryman, and H-Field from the Aberdeen Proving Grounds in Aberdeen, Maryland. The terrain that the vehicle model operates upon is a terrain elevation database derived from, and correlated with, the graphical terrain database. Higher frequency terrain undulations are introduced in the correlated elevation database in order to excite the vehicle vibration modes.

Current work in developing the capabilities of the WHLS Lab are structured with the purpose of being able to evaluate Future Combat System (FCS) contractors models of conceptual vehicles and substantiate performance claims made by contractors through modeling and simulation. Some capabilities that are currently being developed are:

- High-resolution terrain
- Off-road vehicle-soil modeling
- Collision detection and the effects of obstacles on vehicular mobility
- Unmanned ground vehicle simulation experiments
- Advanced cooperative simulation
- Improved integration of real-time and non-real-time, high-fidelity simulations
- Improved model interfacing techniques
- Mitigation of performance-degrading motion effects
- Increased involvement in the Automotive Research Center (ARC)

Some of these topics have well-defined plans for implementation and others are problems that the WHLS Lab is struggling with – such as real-time vehicle-soil modeling and improved interfacing techniques. The remainder of the paper contains a discussion of each one of these topics. It is hoped that in discussing these topics, the WHLS Lab will inform the public of its activities and a dialogue will ensue through which the WHLS Lab will be able to significantly improve its capabilities.

High-resolution terrain

Although the IGs used in the WHLS Lab are state-of-the-art they are still not capable of rendering the detail which the human expects to see in the virtual world. This fact, combined with the idea that a lot of military simulation is done with "puck" or "brick" models, results in the fact that most available databases are sampled for economy of rendering on the image generators and for minimization of size. Since the WHLS Lab utilizes high-fidelity dynamics and motion simulators as core components of a typical simulation, it is necessary that a higher resolution terrain skin be used. Terrain features generally fall into the categories shown the Table 2.

Table 2 Terrain Features in Typical Simulations

Terrain feature wavelength	Simulation impact(s)	Visibility of features	IG rendering
> 30 m	Affects line of sight Exercises power train.	Obvious	Global polygonal representation
5 m – 30 m	Certain cut-in features such as river beds, roads, berms, etc. May affect line of sight. May excite vehicle suspension	Clear	Local polygonal representation
~0 m – 10 m	Features representative of terrain roughness	3-D features hidden	Phong shading and bump map textures

The WHLS Lab will use the Harmony IG, with its Phong shading capability with bump map texturing to represent "micro-surface terrain roughness" visually and engineering level vehicle models to produce appropriate vibration response to the operator. In order to provide the proper excitation to the vehicle dynamics models, however, the GVSL must create a correlated terrain elevation map that contains continuous elevation post data. The WHLS Lab is developing a method to use Non-Uniform Rational B-Splines (NURBS) surface patches that are superimposed upon the base graphical terrain database (15). The result is a continuous resolution terrain elevation database.

Improved Off-road Vehicle-soil modeling

The GVSL is primarily interested in off-road vehicle behavior and must be able to account for the effects of deformable soil on vehicle mobility. WHLS Lab models do not currently have the capability of handling deformable surfaces under the track pads or wheels of vehicle models – the models have the same tractive capabilities whether they are on a hard concrete road or in an patch of deep mud.

The current standard in mobility analysis used by the Army is the NATO Reference Mobility Model (NRMM). NRMM is based largely upon empirical relations derived from data that has been obtained from vehicles running on "typical automotive running gear" in sizes ranging from the HMMWV on up. This does not account, however, for any unique running gear configurations that the Army may utilize in the next generation of weapon systems such as n-wheel, in-hub motor hybrid-electric drive systems with skid steer (differential torque steer).

STI, through the previously mentioned SBIR contract, is developing vehicle-soil relations based upon a variation of Bekker's equations that the GVSL WHLS Lab will use for its real time experiments, however, GVSL capabilities in the area of deformable surface vehicle-soil interaction modeling must be improved beyond the typical Bekker Formulation in order to evaluate the mobility of future Army off-road ground platforms - both manned and unmanned. This is a large problem in general – partly due to the large variations in soil properties from one location to another and a lack of complete knowledge of the behavior of soil being traversed by ground vehicles – in particular, small, lightweight vehicles. The problem is complicated further by introducing lightweight robotic vehicles with unconventional driveline configurations into the problem. It is a bigger problem in real-time

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simulation due to the strict execution time requirements. One possible solution to the unique problems of real-time is to run high fidelity, non-real-time models to generate "empirical data" for lightweight vehicle systems and use this data to create a parametric relation that is subsequently used in the real-time simulations.

With future Army requirements of unprecedented mobility characteristics and lightweight robotic vehicles, physics based methods must be developed for the GVSL to effectively measure mobility of future weapon systems. The GVSL is adding resources internally, and is also working with the Army Corps of Engineers, industry - currently through the STI SBIR, and research institutions - currently through the Automotive Research Center (ARC) and a National Science Foundation Industry/University Cooperative Research Center (I/UCRC) for Virtual Proving Grounds - to solve this significant problem.

Collision Detection and Obstacle Effects

Mobility of ground vehicles involve the ability to travel from point A to point B. Impediments to mobility include steep slopes, terrain surface effects, and obstacles. The performance of a ground vehicle when it encounters impediments to vehicular mobility resulting from steep slopes - vehicle rollover stability and hill-climbing ability - are already included in the current WHLS Lab vehicle dynamics models. The effects of soft-soil on vehicular mobility are planned as a high-priority, near-term improvement and was discussed in the last paragraph. The effects of obstacles, such as fabricated structures, large rocks, trees and other objects, are currently being added to the WHLS Lab models. An "objects database" is being derived from the graphical database. The object database contains the type of object, the location of the object, a proximity radius and some type specific information that gives more detail on the boundaries of the objects, or some detail that is used to generate the forces that influence the vehicle. (Figure 7 describes the databases that are included in a typical WHLS simulation).

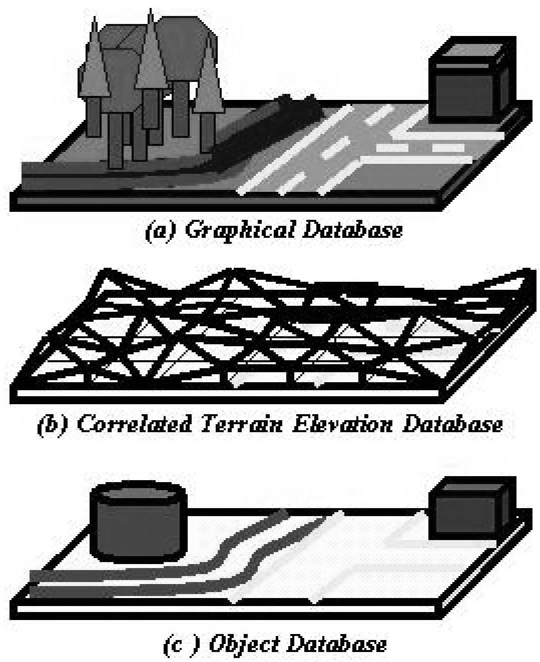

FIGURE 7 : Terrain Databases

(a) *Graphical Database*, the basic database to which the others are correlated.
(b) *Correlated Terrain Elevation Database*, contains elevation data and soil information.
(c) *Object Database*, contains information on impediments to vehicular mobility

The obstacle model consist of an interference manager that keeps track of the location of all the ground vehicle entities in the simulation along with knowledge of the object database described in the previous paragraph. The interference manager monitors the position of each entity and compares the position of each individual entity to the proximity radius of each object and the other vehicle entities. The vehicle model queries the interference manager to determine when it is in close proximity to a mobility-impeding obstacle. If so, a closer check is done that uses obstacle type-specific information to determine positive contact. The vehicle model then calculates and applies the impeding force based upon the obstacle type, any type-specific descriptive information and internal obstacle routines that define the force relations.

Unmanned Ground Vehicle Simulation Experiments

Recent efforts in transforming the Army into a lightweight, highly mobile, network-centric force has motivated significant research into the role of unmanned robotic vehicles in the future battlespace. Strangely enough, the technologies that are developed for use in warfighter-centered simulation experiments also apply directly to robotic simulations. Many of the robotic simulations being performed today involve investigations of teleoperated or semiautonomous control – both of which involve human control to some degree. In the abstract sense, all warfighter in the loop simulations could be considered tele-operation since the operator is not physically present within the vehicle being operated.

Though the underlying theme in this entire paper is that we want to provide the warfighter with the most realistic representation of the real-world situation possible, what we are really developing is an accurate representation of the world external to the operator – whether the operator is a human or a set of autonomous control algorithms and sensors. It follows that virtually the entire WHLS Lab, though developed for human-centered simulation, is entirely applicable to unmanned robotic system analysis. The vehicle dynamics models are identical whether the system is manned or unmanned. Visual sensor models (and hardware) can be stimulated by the same graphical, terrain elevation, and obstacle databases used in the WHLS Lab. Autonomous control algorithms (and driver models) can be developed and tested using the visual sensor models and the vehicle dynamics, mobility, and obstacle models. The requirement for a human controller can even be easily removed once a sufficiently complete set of sensor systems and autonomous control algorithms are included in the platform model. What you have then is an intelligent mobility system model of an unmanned ground vehicle system. Add networking and communication models to the system and you have the capability of including manned and unmanned systems in a distributed simulation that may be used to evaluate ground systems concepts such as the Army's Future Combat System (FCS).

In order to define the missions that unmanned vehicles can perform effectively and develop the robotic systems that may best accomplish these missions, simulation experiments utilizing unmanned ground vehicles are being prepared. The RDEC Federation is an effort of several Army Material Command (AMC) Research Development and Engineering Centers (RDEC) to utilize distributed simulation to bring together models and hardware developed at various RDEC laboratories and research centers together into a single experimental frame within which entire mission plans may be executed. The WHLS Lab is participating in these experiments through a Vehicle Dynamics and Mobility Sever (VDMS).

The Vehicle Dynamics and Mobility Server (VDMS) is a complete, interactive ground vehicle platform model that executes on the TACOM-TARDEC High Performance Computing (HPC) Distributed Center assets and communicates over a network with other entities in a larger distributed simulation. The ground platform model is a complete vehicle system in the sense that it contains the basic set of "automotive" ground vehicle subsystems – powertrain, suspension, tire/tracks, steering, brakes. The model is driven from a remote location through the use of a set of waypoint vectors and a set of desired speeds associated with each waypoint. The model attempts to acquire the defined waypoint at the speed given. The ground platform model then reports information to other entities in the simulation. Included in this information are the vehicle position, orientation, and forward speed.

Advanced Cooperative Simulation

Under a US Army NAC Dual Use Application Program (DUAP) contract, the GVSL, NADS-SC and John Deere Corporation are developing the capability of cooperative, simultaneous, interactive, operator in the loop simulations integrating the WHLS Lab motion simulators and the NADS simulator. The goal of the effort is to show the capability of having engineering level of detail simulations operate together over a network sharing common libraries of ground vehicles and terrain databases, and to show the capability of using the motion simulator laboratories remotely for design optimization studies involving warfighter-centered experimentation (13). The end state of the effort will be the capability to execute an experiment at either site (or both sites) and view, at either site (or any site), performance characteristics of a human operated vehicle system. Parameters of the vehicle may be modified remotely and the effect of the modification will immediately be realized in the vehicle performance.

A recent DUAP experiment (July 2001) performed at the WHLS Lab involved displaying a real-time stress contour plot of a HMMWV control arm during a real-time simulation that involved interacting vehicles (three vehicles were demonstrated), each operated from independent driver stations. This demonstration emphasizes the design nature of the experiments and is a good example that demonstrates the GVSL's emphasis on the term "engineering" in "real-time, distributive, engineering simulations".

A previous experiment (May 2000) demonstrated the use of the WHLS Lab operator in the loop capabilities from a remote location. A tracked vehicle driver (at the WHLS Lab in Michigan) was immobilized in a dry riverbed, unable to climb the steep slope. An engineer (at NADS-SC in Iowa), using notional visual design software applied a multiplication to the maximum available torque until the driver was able to climb the side of the riverbed. The engineer at NADS-SC was able to view the vehicle speed and was able to determine, in real-time, the effects of a modification of a design parameter (symbolized in this contrived experiment by directly altering the engine torque). This demonstrates the utility of using expensive, high-performance, human-centered simulation facilities such as the GVSL WHLS Lab and the NADS-SC for design optimization studies involving the human operator without having the design engineers present at the motion laboratory.

A final demonstration is planned for late 2001. A hybrid electric HMMWV will be driven in the WHLS Lab by an operator on the RMS utilizing full motion and the WHLS real-time simulation environment. A hybrid electric Jeep Cherokee will be driven at NADS-SC utilizing the full NADS real-time simulation environment. Both drivers will be able to visually see the other. An engineering tool will display contour plots of the stresses in certain predefined components (as in the July 2000 demonstration). Another engineering tool will be displaying pertinent hybrid electric powertrain performance, and, possibly, will provide the means for someone at either lab to alter some hybrid powertrain design parameters during the simulation.

This DUAP demonstrates how the GVSL WHLS Lab could support acquisition of major Army systems by working with contractors to investigate system performance of proposed systems at many levels – total system (including the operators), subsystem (for example, the hybrid electric power management systems), or component (structural component durability) in a motion environment. It also removes the requirement that the contractors be present at the test site as experiments can be performed and data viewed in real-time over a network.

Integration of Real-time and Non-real-time, High-fidelity Simulation

The GVSL, having a long tradition of high-resolution, non-real-time vehicle dynamics modeling and simulation expertise and a large library of vehicle models, is trying to establish ways to combine the non-real-time capabilities and the real-time capabilities into a synergistic system. Primarily, this consists of using DADS models as the basis for the development of a real-time set of vehicle models. This is done in two ways. Using the HPDC multibody dynamics code described above, the basic data file that describes the high-resolution DADS models is converted into a set of data and functional elements that HPDC understands. If the DADS modeler follows certain conventions in developing the DADS vehicle model, the conversion from a DADS model to a HPDC model is seamless and results in the automatic conversion of the vehicle chassis and suspension, steering, and tire/track subsystems from the DADS model to the HPDC framework. For the system level dynamics codes, a set of test procedures is being defined that allows a set of vehicle dynamics parameter inputs to be derived from a DADS model. In effect, this is a virtual characterization of the high-fidelity models.

Looking at the relationship from the other end, the real-time operator in the loop capabilities of the GVSL are expected to be used to improve the accuracy and the breadth of virtual evaluations that may be handled through the high-fidelity modeling methods. The toughest part of the system to model is the non-deterministic behavior of the operator. In order to avoid modeling the driver, the GVSL will deduce a real-time model from the high-fidelity DADS model as described in the last paragraph, utilize that reduced model in an operator in the loop experiment and capture the operator inputs. The operator inputs will then be used to drive the high-fidelity models of the ground vehicles. This, in effect, allows the non-real-time vehicle models to be "driven" by a warfighter. A challenge exists in the sense that, since you are operating two different models with the same set of operator controls, their paths will diverge. A method of synchronizing the trajectories must be developed. If this can be done satisfactorily, it will not only improve the capabilities of controlling the high-fidelity vehicle dynamics simulations, but it could, theoretically, allow for the notional real-time operation of highly detailed models that run much slower than real-time.

Improved interfacing techniques

In addition to in-house developments, the GVSL obtains models from many sources and at many levels of system topology: Army weapon system developers; research centers, such as the Automotive Research Center (ARC) and the National Science Foundation Industry/University Cooperative Research Center (I/UCRC) for Virtual Proving Grounds; contracts such as the Small Business Innovative Research program or the Dual Use Science and Technology Program; are all sources of models at both the system level and at the detailed component level. A challenge arises in interfacing the models into the WHLS Lab real-time system architecture.

The WHLS Lab real-time infrastructure facilitates well-defined interfaces between interacting subsystems, but the GVSL has not historically defined the interfaces used by the model developers. Wrappers are usually created to mate the contractor interface to the WHLS interface. In practice, this is a difficult process and requires significant support from the original model developer. The GVSL WHLS Lab is beginning to require that its real-time interfaces be followed for the larger subsystems such as graphics, vehicle dynamics, I/O, and sound. Some of these subsystems, however, lend themselves to additional division into modules. One instance is the vehicle dynamics subsystem, which consists of multi-body dynamics, power train, braking, suspension, steering, tires/track, road profile, and soft soil models. The WHLS Lab does not currently have control over these interfaces. This results in a partial solution – higher level subsystem models may be integrated into the WHLS Lab much easier today than in the past, but lower level modules continue to be intensive integration efforts.

It is the GVSL's desire to define flexible and modular interfaces for these modules to facilitate interchangeability. Since it is difficult to anticipate the workings of modules which are yet to be developed without placing crippling restrictions on the modules themselves due to the often tight coupling required for lower level modules, it is important to implement these interfaces based on the physics of the problem. Consider the vehicle powertrain and braking modules. The WHLS Lab powertrain is a straightforward implementation involving the mapping of throttle position and speed to torque. A powertrain interface may reasonably be defined based upon this simple model that would extend well to more complex powertrain models. Even in the simple case, a fairly complete interface is easily assembled that remains valid through the entire possible range of operations. The brake, on the other hand, is usually implemented as a torque that opposes velocity under dynamic conditions. At zero speed, with the brakes locked, typical implementations of a brake model have been subject to pragmatic implementation, rather than straightforward modeling the effects of Coulomb friction. Trying to park a car on a slope becomes a special case that is not handled easily as a general "brake" model. The inevitable result that the WHLS Lab has noticed is that the vehicle does not remain stationary on a longitudinal slope regardless of the braking effort applied. (Though this effect may, in fact, be due to tire slip, the authors blame it on the brake model, nonetheless. After all, it is the parking brake that we are applying, not tire blocks.) The WHLS Lab has a need to define subsystems and modules in an intelligent manner that allow for an easier integration of models from different sources without placing undo restrictions on the internal workings of the models.

Mitigation of Performance degrading motion effects

The Army, as mentioned earlier, is moving towards a highly mobile force that depends upon remote sensing capabilities, long-range firepower, and mobility to provide a large part of its effectiveness. The ability of a warfighter to assimilate large quantities of information, interpret the information and act upon the information in an intelligent and effective manner is a crucial piece of information that, if ignored, could render expensive, complex systems unusable, or cause significant training issues. The GVSL is teaming with the Army Research Lab Human Research and Engineering Division (ARL-HRED) to design investigative studies and determine methods of improving the soldier-system synergy early in the weapon system life cycle. Two areas that are being targeted are the motion sickness issues related to troop transport within the back of a ground vehicle traversing harsh terrain over a long period of time, and command and control on the move – an idea that has been elusive for many reasons in the past (16). The GVSL WHLS Lab and ARL-HRED are poised to provide the Army's Future Combat System (FCS) developers with experiments that will provide a more usable weapon system.

The absobed power and human response work performed at at TACOM in 1960s involved the use of a motion platform that was able to impart basic motions to the occupant Today, the GVSL WHLS laboratory has an operator-in-the-loop simulator that can impart forces representative of harsh, high-speed, off-road terrain. Human vibration can be studied in completely controlled experiments that simulate real-life test programs or operational missions. In the more general sense, human *performance* may now be studied in a completely controlled environment that recreates a real-life situation. The ability of a soldier to assimilate a large amount of sensor data and act appropriately while traveling though rough or complex terrain is now available to the experimenter.

Support to ARC research

The GVSL has been involved with the Automotive Research Center (ARC), a collaboration of eight different research universities, many commercial entities, and the US Army - primarily in technology transfer of ARC developed simulation technologies in the area of real-time simulation and virtual proving grounds. Globally Independent Coordinate (GIC) method of multibody dynamics (17) and advanced numerical methods, including dual-rate integration schemes (18) for solving Differential Algebraic Equations (DAE) have been developed at the University of Iowa and demonstrated within the GVSL WHLS Lab. Dynamic terrain (19) and hybrid electric powertrain system models are expected to be technologies that are transferred in the near future.

The GVSL WHLS Lab has also been assisting ARC researchers in the area of human factors. The RMS has been used in a set of preliminary studies related to “feed-through dynamics” concerning the effect of vehicular motion on the operator’s control inputs. Additional work in the areas of haptic driver’s aid devices and rollover warning devices are planned.

The GVSL has recently been reorganized to fall under the organizational structure of the National Automotive Center (NAC). The ARC is a NAC-funded effort and, as such, the GVSL will become much more active in the ARC in the near future. ARC model technologies will be integrated in the GVSL to a much more extensive level, and the GVSL WHLS Lab will assist human factor researchers from the ARC in use the RMS and the CS/TMBS as both a research tool and as a validation tool for operator/human modeling efforts.

CONCLUSION

The GVSL is able to handle a variety of automotive and military mission module engineering analyses. Non-real-time analysis capabilities and laboratory durability analyses are fairly mature and have been employed by the GVSL for many years. The GVSL WHLS Lab has recently established a basic engineering level-of detail operator in the loop capability and has identified areas that still require further development in order to truly play a significant role in aiding the Army’s transformation to a more deployable, lighter, yet more effective force. Some of the identified areas are well understood and plans are in place to bring about the improvements. Other areas are more challenging and the GVSL WHLS Lab is struggling with alternative approaches to those topics. With the recent initiatives to team with ARL-HRED, the ARC and the RDEC Federation, the GVSL is targeting areas that will have the greatest impact in providing the Army with a capability that best suits the needs of the Army of future.

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