HIGH-FIDELITY GROUND PLATFORM AND TERRAIN MECHANICS MODELING FOR MILITARY APPLICATIONS INVOLVING VEHICLE DYNAMICS AND MOBILITY ANALYSIS

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ABSTRACT

The US Army's High-Fidelity Ground Platform and Terrain Mechanics Modeling (HGTM) Science and Technology Objective (STO) (IV.GC.2003.01) is developing methods to facilitate the creation and application of high fidelity, real-time, ground platform mobility and terrain models. The models are applicable to warfighter in the loop virtual experiments investigating methods of mitigating the effects of motion on soldier performance, for the development and evaluation of conceptual manned and unmanned ground platform dynamic performance and mobility, and as a component of embedded simulation and training systems. This paper provides an overview of the HGTM STO vehicle and terrain M&S technology development effort and a description of the application of the STO products.

1. BACKGROUND

The High-Fidelity Ground Platform and Terrain Mechanics Modeling (HGTM) Science and Technology Objective (STO) is a collaboration between the US Army Research Development and Engineering Command (RDECOM) and the US Army Corps of Engineer Engineering Research and Development Center (ERDC). It involves four organizations; RDECOM Tank Automotive Research Development and Engineering Center (TARDEC), RDECOM Army Research Laboratory (ARL), ERDC Geotechnical Structures Laboratory (GSL), and ERDC Cold Regions Research and Engineering Laboratory (CRREL). The purpose of the HGTM STO is to develop real-time ground platform mobility and terrain M&S technologies and to employ those technologies towards human performance experiments that investigate methods of mitigating the effects of motion on human performance. The main proponents are the US Army Training and Doctrine Commands (TRADOC) Unit of Action Maneuver Battlelab (UAMBL) at Ft. Knox, KY. and the Maneuver Support Center (MANSCEN) at Ft. Leonard Wood, MS. The primary customers are military ground platform technology developers and weapon system designers.

The four year program started in October 2002. The first year consisted of detailed planning of specific capabilities, baselining current vehicle modeling capabilities, a validation effort of current terrain capabilities for vibration predictions (Lamb et al., 2002), and the identification of methods of mitigating the negative effects of motion on warfighter performance. The second year consisted of a set of experiments quantifying the effects of motion on human performance (Meldrum et al., 2004), initial investigation of mitigation effects (McDowell, Draft Protocol, 2004), and an initial implementation of a real-time, physics-based vehicle-terrain interface (Nunez, Nham et al, 2004). In addition, during the first two years, models were applied within the context of an embedded simulation system used to develop crew station technologies, as the high-fidelity ground mobility component for two distributed simulation environments being developed to support distributed experimentation and testing for the US Army's Future Combat System (FCS) (Nunez, 2003 and Docimo et al., 2004), and within an FCS Lead System Integrator (LSI) experiment comparing direct and indirect driving.

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The final two years will consist of continued development of the core vehicle and terrain modeling technologies and further investigation of motion mitigation techniques. The application of the STO products will continue with experimentation in support of external military technology developers, and with the application of the STO products within Army and joint service distributed simulation architecture development and experimentation.

2. HGTM STO TECHNOLOGY DEVELOPMENT

The work being performed under the HGTM STO falls under three pacing technologies; vehicle modeling, terrain modeling, and the mitigation of motion effects. TARDEC is responsible for vehicle model development, terrain database elevation profile enhancements, and the refinement of an immersive motion simulation environment. ARL is responsible for defining motion mitigation effects and providing human experiment design and analysis capabilities. GSL is responsible for the characterization of soils, their effect on mobility, and complex obstacle modeling. CRREL is responsible for all season environments - the effects of snow and freezing and thawing terrain.

The HGTM STO concentrates specifically on real-time modeling and simulation capabilities that support experimentation and analysis using embedded systems including humans (commanders, drivers, and robotic system operators), software (situational awareness software, power system control algorithms, and autonomous navigation systems), and hardware (crew station devices, hybrid power supply systems, and gun turret systems). Higher resolution models that are not capable of real-time execution and lower resolution models that allow large numbers of ground platform entities to be simulated are considered briefly in order to ensure a consistency of vehicle mobility predictions across multiple resolutions.

2.1. Vehicle & Terrain Modeling

2.1.1 High-Resolution Real-Time Models

The goal of the HGTM STO in terms of vehicle models is to provide a vehicle or technology developer with a way to evaluate how effective the design is when employed within an operational environment. Traditionally, vehicle designers work in the world of high-resolution constructive engineering simulations where the human aspect and the operating environment are difficult to quantify. Physical laws that govern subsystem performance may be accurately simulated, but the actual usage of the aggregated system is grossly approximated and the non-deterministic behavior of the human and psychological effects on the human are usually not considered.

In order to fully bring the human operator into a simulation, real-time operation is required. In order to bring design level models into real-time simulations, complicated systems of equations must be solved in an efficient manner. The goal of the HGTM STO is to develop vehicle modeling constructs and equation solution algorithms that allow complex models to be employed within a real-time environment.

Modeling the operating environment in high-fidelity requires a large scale effort and the deployment of a host of subject matter experts that are not traditionally available to the typical vehicle component or subsystems designer. This is solved through distributed simulations that identify subject matter experts in the various functions of weapon systems, allow them to work in their area of expertise, and then connect their models using network protocols. The HGTM STO developers are working with RDECOM, TRADOC, the Army Test and Evaluation Center (ATEC) and with other services in order to include a full high-fidelity battlefield context to simulation experiments.

The HGTM STO emphasizes mobility, so the drive train, suspension, tire/track, and terrain models are the primary component models being advanced.

2.1.2 Composable Models

Most real-time vehicle models developed today for vehicle design applications consist of highly optimized systems of equations that represent vehicles with a generally constant topology. Specifically, they are developed by the automotive industry and consist of four-wheel vehicles with traditional drive trains and steering systems operating over hard surfaces. Military ground platforms must operate over widely varied terrains, which results in a large set of possible wheeled and tracked configurations to deliver power to the ground.

In the traditional method of developing real-time ground vehicle models, a basic vehicle configuration is developed, the equations of motion are identified, the resulting set of equations are examined in great detail, and solution methods are developed that are highly optimized. Models of different vehicles are developed by modifying parameters in the optimized model, which works well if the same basic topological structure exists between the models. This parameterized approach does not work well, however, for the military situation where the vehicle configurations are widely varied. The challenge is to develop a means to model components to a high level of resolution and create methods to connect the various components into a system level model in a way that optimizations are automatically included. In other words, the HGTM STO is developing the means to develop optimized composable models.

Interfaces are being defined between components and subsystems that allow a vehicle modeler to easily create new models. The basic philosophy is to develop separate component or subsystem models and define interface methods that mirror the physical interfaces, yet are transparent to the model developer.

2.1.3 Continuous Resolution Terrain Elevation

HGTM STO experiments require that the human operator be subjected to motion that is representative of real-world operations. The primary motion platform used in motion experiments is able to handle 2G maximum transient acceleration signals with a 3 dB frequency of 40 Hz. In order to fully utilize the hardware capabilities, the vehicle models should provide vibration motion up to that range. Typical vehicle models do not predict such vibration levels, and typical military digital terrains do not contain elevation profiles of sufficient resolution to excite models up to that range. In order to solve this problem, the HGTM STO includes an effort to develop a continuous, analytical description of a terrain profile that statistically represents the real world terrain (Reid, 2002). Spline functions are overlaid upon the lower resolution terrain surface polygons with the end result that the digital terrain contains sufficient spectral content to drive the vehicle vibration models. In essence, bumps are sprinkled on large polygonal surfaces (Figure 1). The vehicle models then act as filters, just like the real systems, that transmit the energy to the motion simulator which then imparts the energy to the occupant.

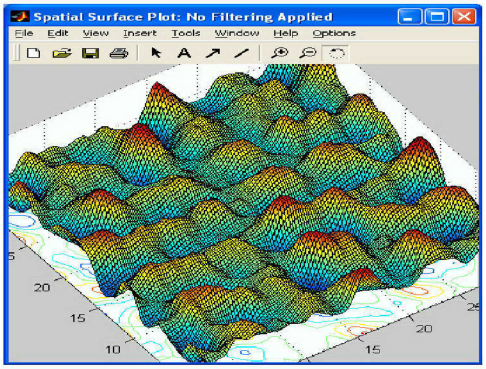

Figure 1: Continuous Resolution Elevation Profile (Morrison et al, 2004)

2.1.4 Physics-Based Real-Time Terramechanics

The interaction between a mobile ground platform and a deformable terrain surface is perhaps the most important aspect of ground mobility to model accurately for off-road vehicles. Ironically, it is also the most difficult and the least understood in terms of deterministic physics-based modeling methods. The tire is a complex force generating device; terrain is a complex, deformable boundary condition. Predicting the interaction between the tire and deformable terrain presents a significant technical challenge. The same arguments apply for tracked vehicle systems.

The single most challenging aspect of the HGTM STO is to predict this interaction, and to do so within the constraints of real-time simulation. In addition, it is desirable to be able to define a modular interface between the vehicle and the terrain that allows the vehicle models and the terrain models to be developed independently and in a conceptually separated manner. The approach is similar to the concept of separating the subsystems and components that make up a vehicle mobility system using interfaces that parallel physical interfaces (Section 2.1.2).

The general theory used in the HGTM STO development is that a vehicle contact patch flows over the terrain with a given pressure and velocity distribution. The patch is divided into nodes with associated areas. The entire patch travels with a given velocity and each node contains a pressure, area, and slip velocity. The initial implementation of predicting the forces between the tire and terrain uses the WES numeric, developed by the GSL, which is based upon laboratory soil bin tests, and CRREL winter traction equations developed from experimental data (Richmond, Jones, et al., 2004). Future work will consider three-dimensional lumped parameter models of the terrain (Creighton and Walker, 1998).

2.1.5 Deformable Terrain Effects

Previously we stated that the vibration response of a vehicle is influenced by the profile of the terrain and that the forces that generate locomotion and direction are influenced by the terrain surface characteristics. Deformable terrain influences are also important and they affect the entire spectrum of vehicle response – vibration, forward acceleration, top speed, braking, turning capability, and directional stability.

The terramechanics methods described above to predict the forces between the tire/track and the terrain also result in a calculation of the tire/track sinkage into the terrain. The value is retained as a “delta-z” layer throughout the simulation. This allows rearward traction elements to experience the deformation created by forward traction elements, follow-on vehicles to experience terrain damage from lead vehicles, and small vehicles to experience ruts created by large vehicles. In addition, the terrain surface characteristics used in the HGTM STO are modified with simulated trafficing (Shoop et al, 2004), thereby allowing the effects of weather to be added to the simulation.

2.1.6 Complex Obstacles and Urban Mobility

Urban terrain, from a ground platform mobility point of view, is a set of complex obstacles along with some multi-elevation surfaces (including building interiors with steps). The basic building blocks of the HGTM STO – high-resolution vehicle models and terrain elevation profiles, along with collision detection and response and the negotiation of obstacles, will be assembled together in order to study ground maneuver in urban operations.

The HGTM methods being developed for obstacle negotiation consider three situations. The first is a static, nondeformable obstacle being traversed (or impacted) by a dynamic vehicle. This is an extension of the vehicle-terrain interface, along with collision detection and response capabilities. The second case involves movable objects. The HGTM STO approach to this problem is to set up various obstacles in a real world situation, attempt to move the obstacles with real vehicles, and measure the force required to move the obstacle. These experiments will then result in a set of parametric equations that will be used for movable obstacles. The third and most challenging case of obstacle negotiation is deformable obstacles. The approach of the HGTM STO to this problem will be a combined structural mechanics solution and experimental relation solution. Structural solutions will be employed where force-deformation relations are known. Experimental data will be used for other cases, such as rubble piles, with the, as yet unsolved, problem being the characterization of the rubble pile (or, in a general sense, the characterization of the deformable obstacle).

2.2. Motion Effects Mitigation

The third HGTM STO pacing technology involves the use of the mobility models within human experimentations to examine the effects of motion on warfighter performance and the efficacy of motion mitigation techniques. Mitigation techniques being considered for investigated involve both “machine” modifications (ground platform chassis and suspension design, visual devices such as virtual windows and artificial horizons, three dimensional audio, a variety of operator control devices and displays) and “man” modifications (autogenic training techniques and self-efficacy methods) where the warfighter is taught ways to be more aware of his actual performance and to control his behavior internally to reduce the negative effects of motion. This paper addresses the vehicle and terrain modeling aspects of the HGTM STO and leaves further discussion of motion mitigation techniques to a separate paper.

3. APPLICATION OF HGTM STO PRODUCTS

3.1. Distributed Mobility Model Component

The vehicle and terrain models being developed under the STO are used for internal warfighter in the loop experiments, but are extensible for use as semi-automated forces or as robotic platform models. The basic vehicle and terrain models, with embedded driver models are packaged with a well-defined external interface (Figure 4, next page) that allows them to function as a high-fidelity mobility component of a larger simulation. This product is called the Vehicle Dynamics and Mobility Server (VDMS) (Brudnak et al., 2002).

VDMS entities are controlled via desired speed and heading instructions, a series of waypoints (route), or tele-operation commands (brake, throttle, steer, and gear). VDMS may operate stand-alone, or it may be used within a distributed simulation environment and used to update ground platform mobility state values. The stand-alone version provides an off-line analytical tool and is used within the HGTM STO Verification & Validation (V&V) process. The distributed version is being used in the RDECOM Modeling Architecture for Technology Research and Experimental (MATREX) and the Development Test Center (DTC) Virtual Proving Ground (VPG) projects (Figure 2).

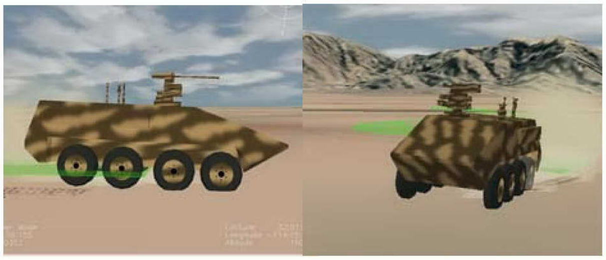

Figure 2 VDMS Executing Hard Brake and Turning for DTC VPG Operations (Docimo et al., 2004)

Replacing the driver models within VDMS with real embedded autonomous navigation system (ANS) software allows VDMS to replicate unmanned ground vehicles. For use in the development and evaluation of robotic vehicle concepts, the ground vehicle models may be connected to terrain sensor models (or provided with equivalent data) and integrated with embedded sensor fusion and autonomous control algorithms. This could include either real-time or high-resolution models depending on the particular experiment or whether the sensor fusion or autonomous control algorithms require real-time systems.

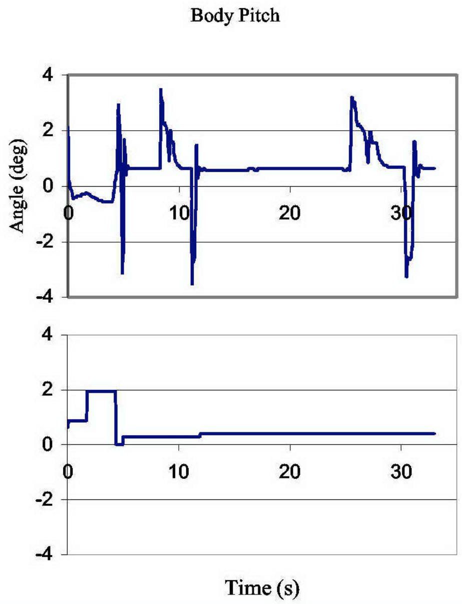

Figure 3 Comparison of VDMS (top) and OneSAF Test Bed Pitch Motion

HGTM STO developers are searching for ANS software and sensor models in order to demonstrate the capability for robotic system development.

The current application of VDMS is to establish a method of improving the resolution and fidelity of the ground vehicle models that are used in computer generated forces, when needed (Figure 3). This task primarily involves either a large number of computer processors or a significantly reduced order model that is consistent with the real-time and high-resolution models (which should be consistent with each other). High performance computing facilities are used by the STO developers to execute vehicle models, and multiprocessor capabilities are being used in order to execute large numbers of ground platform entities within a distributed environment. It should be noted that higher resolution models are not always required, and when not required, the complications associated with increasing resolution are not usually worth the effort.

3.2. Warfighter Machine Interfaces & Vehicle Design for Improved Human Performance

The high fidelity motion simulators combined with the vehicle and terrain models generated by the HGTM STO are used within the scope of the HGTM STO towards the quantification and evaluation of human performance within a motion environment (Nunez and Paul, 2004).

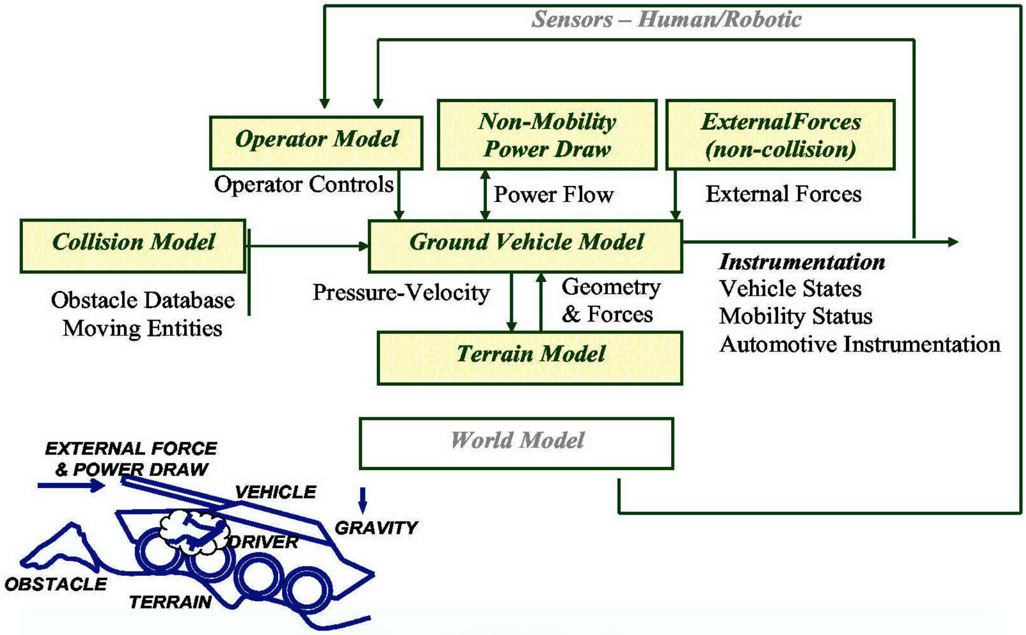

Figure 4 VDMS Interfaces

Once these measurements are possible within a controlled laboratory environment, vehicle design efforts that take into account the human aspect of the vehicle system are possible at the total system level. Design efforts include the warfighter machine interface in terms of display devices, information contained in the displays, operator controls, and three-dimensional audio.

Specific experiments already executed or planned for the remainder of the HGTM STO include:

1. Occupant reach and tactile operation in a dynamic environment
2. Influence of vehicle design (ex. active, semi-active, passive suspension) on driver, gunner, commander performance (Zywiol and Oldaugh, 2004)
3. Influence of display type (flat panel versus head mounted display) on driver and/or commander performance
4. Influence of display device field of view on driver performance
5. Teleoperation of a robotic vehicle from a moving platform and methods of mitigating motion sensory mismatch effects on the operator (Hill et al., 2004)
6. Methods of control for multiple robotic assets including mobility, surveillance, and targeting tasks
7. Use of three-dimensionally audio effects and speech recognition technologies towards enhancing system control
8. Methods of various levels of adaptive automation towards control of robotic platforms.

3.3. Army Power Budget Model and Power System Duty Cycle Experiments

The HGTM STO developers are working with the Power and Energy Hardware in the Loop Systems Integration Laboratory STO and the Pulse Power for FCS STO developers in order to develop what is known as the Army Power Budget Model. The Army Power Budget Model will integrate dynamic models and hardware components of power producing systems (i.e. hybrid power train systems), a hybrid set of dynamic and static power consumption models and hardware components (i.e. mobility, survivability, lethality, C4ISR subsystems), and a library of mission profiles (duty cycles) to which future military vehicles will be subjected. The integrated set of models will be designed to provide both a desktop analysis capability and a distributed simulation capability.

Future vehicle platforms will not only serve typical mobile combat and tactical functions, but will also serve as a mobile power source for the future force. In order to effectively design a power management system for the US Army's Future Combat System, accurate estimates of power loads throughout the complete range of operations are required. Little data exists on power flows involved in current military operations and less data exists on the power requirements of a FCS vehicle. What is known of FCS operations to date has been determined from inventive thinking combining concepts of operations and extrapolation of the current state of technology. New concepts and force structures have been investigated using modeling and simulation.

The HGTM STO products will be used to estimate mission profiles, or duty cycles, using constructive and virtual simulations. Data from RDECOM and TRADOC simulation experiments will be used to estimate the power requirements during future army operations. The experiments will involve FCS operations of movement to contact and decisive operations. Three simulations will be employed for this project.

The first duty cycle will come from Combined Arms and Support Task Force Evaluation Model (CASTFOREM). An FCS scenario will be executed using CASTFOREM and the activity of each vehicle will be examined. The actions of these vehicles during the simulation will be identified as the first duty cycle developed under this project.

The second set of duty cycles will be developed through the extraction of data from a TRADOC warfighter exercise. Similar to the CASTFOREM experiment, the "activity" of a select set of vehicles will be examined and the power consumption associated with mobility, lethality, survivability, and battle command will be examined to develop a duty cycle.

The third duty cycle estimate will come from a simulation experiment that will connect a virtual systems integration laboratory in Warren, MI to a hybrid power train hardware systems integration laboratory in Santa Clara, CA, thereby involving significant hardware components and embedded software control systems. VDMS will provide mobility functions with the power train components being provided through a connection to the Santa Clara, CA systems integration laboratory. VDMS will operate within a TARDEC developmental crew station with an embedded simulation system used to represent non-mobility systems and the external environment. Unlimited power will be available for non-mobility systems in order to determine power requirements.

The three sets of experiments range from broad-scoped with large numbers of low resolution entity models to narrow-scoped with small numbers of high resolution entities. The end goal of these experiments is to provide mission profiles, or duty cycles, to be used within the desktop version of the Army Power Budget Model. Then, an optimized power management algorithm will be developed and the third experiment will be rerun without the assumption of unlimited power for non-mobility systems in order to evaluate the effectiveness of the control algorithm towards meeting the power requirements.

3.4. Virtual Evaluation Suite (VES)

The off-line, stand alone version of VDMS described above will be used both as an analysis tool to evaluate vehicle designs and as the core V&V tool for HGTM STO developed models. Since VDMS is flexible in how it is controlled, a wide set of simulated test conditions may be set up and executed.

This is a tool is called the Vehicle Evaluation Suite (VES) (Nunez et al, 2002). The goal of this project is to create a virtual evaluation course that contains a full spectrum of automotive performance tests over geographically distant terrains and under various weather conditions. Standard output reports and full design and performance characteristic sheets will be automatically generated. The VES is a test bed within which the vehicle modeling technologies developed under the STO are tested and evaluated.

Five sets of test suites are planned at this stage;

1. Interface Compliance/Common Problem Test Suite: check the vehicle model interface compliance and common problems
2. Vehicle dynamics suite: evaluates typical vehicle stability, handling, and ride and shock quality
3. Soft-soil Mobility suite: evaluates soft-soil capabilities in varying soils and soil conditions
4. Obstacle suite: evaluates obstacle negotiations including gaps and walls and complex obstacle groupings
5. Power train suite: evaluates propulsion system performance (acceleration and braking) and fuel consumption/power management.

3.5. Unmanned Ground Vehicle Demonstrations

HGTM STO developers are developing a series of demonstrations in order to set timelines for technology development efforts and to demonstrate capabilities (Brudnak, Draft Demo Plan, 2004). The demonstration is based upon manned/unmanned vehicle scenarios specifically intended to mimic the Robotic Follower (RF) mission. The scenario includes one manned vehicle and four robotic vehicles operating in two configurations – a "pull" and a "push" configuration. Several integration thresholds have been defined. Each adds a capability package to the HGTM simulations, most of which were previously discussed in this paper. The final integration threshold goal includes all STO developed vehicle and terrain modeling technologies and inserts them into a large scale distributed simulation environment involving the robotic system configurations operating within an urban environment.

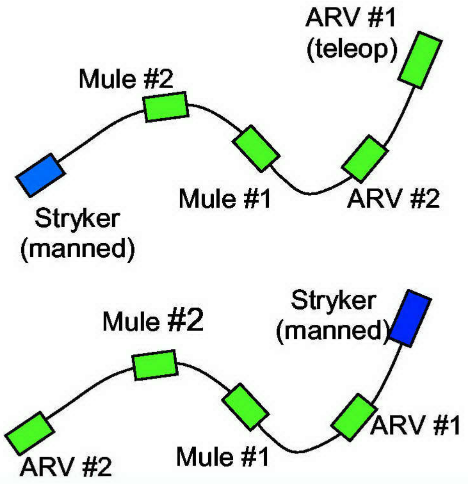

Figure 5 "Push" (Top) and "Pull" (Bottom) Configuration of Robotic Convoy

4. SIMULATION AND SIMULATOR VALIDITY MEASUREMENTS

The ultimate goal of the HGTM STO is to provide models of FCS ground platform conceptual chassis & suspension designs – and mock-ups of crew station designs - with a resolution/reconfigurability that is sufficient for an engineer to perform design trade studies (and for the government to provide an objective evaluation of the conceptual design) within a controlled laboratory environment. The ultimate metric by which the HGTM STO should be measured is the extent that the tools developed by the STO developers are successful in achieving this goal, along with the extent that measured human performance is improved through motion mitigation techniques.

The method by which such a task is measured is not straight forward, however. The validation efforts of the HGTM STO are two-fold. First is a bottoms-up approach in which each component of the simulation is compared to a real-world referent and the degree to which the simulation differs from the referent is both measured and the source of error is identified.

The second method of simulator validation is an "end effect" method that directly identifies how well STO experiments capture human performance effects. A simulation experiment is created that, to the greatest extent possible, recreates a real world experiment. The human subject's performance on a given task is measured during both the simulated experiment and the real experiment and, again, a comparison is made. In addition, the HGTM STO validation methods for the human experiments also consider longer lasting effects on human performance. Immediately upon completing the main task within a vehicle, a set of questions and fairly simple tasks are performed by the subject. The identical set of questions and tasks are used for both the real world experiment and the simulated experiments, and the results of the two situations are compared.

CONCLUSIONS

The HGTM STO is a collaborative effort between experienced mobility modeling organizations and human factors subject matter experts. The primary STO contributions to the advancement of science and technology are:

- Insertion of design level of resolution models into operational scenarios
- Quantification of the effects of motion on warfighter performance
- Scientific evaluation of several methods of reducing the effects of motion on warfighter performance.
- Exploring the boundaries of the level of design resolution modeling that can occur in a real-time simulation environment
- The development of a physics-based terrain and vehicle-terrain interaction model
- Investigation into the possibility of a substantially composable set of design level resolution subsystem and component models
- Application of real-time ground mobility models to large scale distributed simulation efforts and external human in the loop experimentation

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