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Soldier/Hardware-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 2

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Soldier/Hardware-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 2

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Keywords:
Motion base simulator, hybrid electric power system, man-in-the-loop, hardware-in-the-loop, long haul.

ABSTRACT: *This paper describes a human-in-the-loop motion-based simulator interfaced to hybrid-electric power system hardware both of which were used to measure the duty cycle of a combat vehicle in a virtual simulation environment. The project discussed is a greatly expanded follow-on to the experiment published in [1]. This paper is written in the context of [1] and therefore highlights the enhancements. The most prominent of these enhancements is the integration (in real-time) of the Power & Electric System Integration Lab (P&E SIL) with a motion base simulator by means of a "long haul" connection over the Internet (a geographical distance of 2,450 miles). The P&E SIL is, therefore, able to respond to commands issued by the vehicle's driver and gunner and, in real-time, affect the simulated vehicle's performance. By thus incorporating hardware into a human-in-the-loop experiment, TARDEC engineers are able to evaluate the actual power system as it responds to actual human behavior. After introducing the project, the paper describes the simulation environment which was assembled to run the experiment. It emphasizes the design of the experiment as well as the approach, challenges and issues involved in creating a real-time link between the motion-base simulator and the P&E SIL. It presents the test results and briefly discusses on-going and future work.*

1. Introduction

The Army has been developing hybrid electric propulsion technology to assess and use its many advantages. Among these advantages are better fuel efficiency and the ability to maintain "silent" operations. As such, many alternatives exist in the implementation of such systems in terms of architecture, component sizing, energy management and control. Anticipating all of these choices, the Army initiated the Power and Energy Combat Hybrid Power Systems (P&E CHPS) program as a TARDEC effort to advance and develop hybrid electric power and propulsion technology for application to combat vehicles. A major goal of the program includes designing, developing and using a full-scale hardware/software-in-the-loop Power & Energy System Integration Laboratory (P&E SIL or just SIL for short). The SIL is a full-scale combat vehicle power system with programmable dynamometers for applying road loads to the propulsion and power system. A photograph of the SIL is shown in Figure 1. When combined with high-fidelity vehicle and terrain

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1. REPORT DATE **24 JAN 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Soldier/Hardware-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 2**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Mark Brudnak; Mike Pozolo; Victor Paul; Syed Mohammad; Dale Holtz; Wilford Smith; Marc Compere; Jarrett Goodell; Todd Mortsfield; Andrey Shvartsman**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000**	8. PERFORMING ORGANIZATION REPORT NUMBER **16948**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC** 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **16948**

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

13. SUPPLEMENTARY NOTES
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	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**17**	

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Figure 1. The Combat Hybrid Power System – Power & Energy System Integration Laboratory (P&E SIL).

models, the SIL can be used to predict the reaction of the power system to mobility loads as well as non-mobility loads due to interaction of the vehicle with its environment. The product of the P&E program will be a compact, integrated hybrid electric power system that will provide efficient power and energy generation and management suitable for spiral integration into the Future Combat System (FCS) Manned Ground Vehicle (MGV) program.

In order to effectively use the SIL to design, develop, and test a hybrid electric power system for advanced combat vehicles, accurate estimates of a duty cycle are required. The TARDEC P&E program is addressing this situation by measuring advanced combat vehicle duty cycles. These duty cycles are derived from the virtual representations of advanced combat vehicles and combat scenarios using both war fighter-in-the-loop and power system hardware-in-the-loop simulation described in detail in the remainder of this paper. This project combines engineering level power supply system with performance-level models of power consumption devices and combines them within a war fighter simulation that represents several tactical scenarios.

For our purposes a military vehicle's duty cycle is specific to the mission and platform type but is a design- and configuration-independent representation of events and circumstances which affect power consumption. Such events and circumstances encompass (1) vehicle operation such as speed, grade, turning, turret/gun activity, and gun firing plus (2) external scenario components that affect power consumption like incoming rounds, ambient temperature, and soil conditions. The event inputs can be distance-based when the vehicle is moving or time-based when the vehicle is stationary, or even triggered with some other state condition.

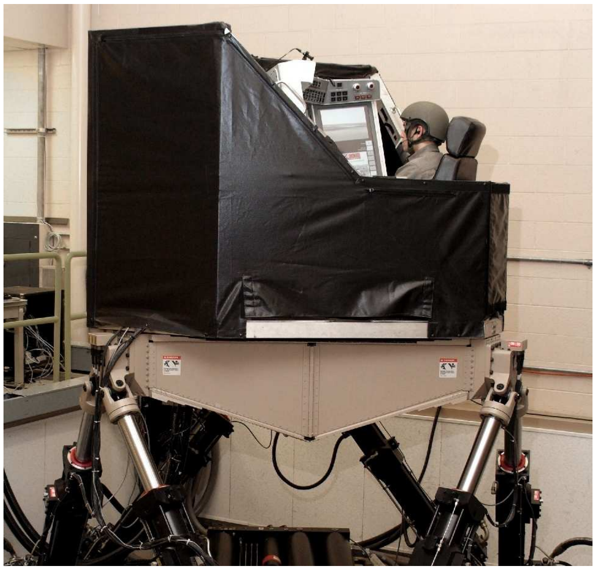

Figure 2. Ride Motion Simulator.

In order to measure such a duty cycle, TARDEC has been building a motion base (see Figure 2) war fighter-in-the-loop simulation capability in which soldiers can virtually operate their vehicles in relevant combat scenarios. This simulation is then used to perform experiments in which duty cycle information is captured. This series of experiments has been called the Duty Cycle Experiments (DCEs). The first such experiment (DCE1) was conducted in November – December 2005 and is described in [1,2]. After the completion of DCE1, another experiment was designed and executed in June – July 2006 which was called DCE2. This experiment went beyond the capabilities of DCE1 in several respects, one of which was the long-haul integration of the SIL into the simulation design. The fundamental challenge in this regard is that the motion base, the Ride Motion Simulator (RMS), and the SIL are geographically separated by 2,450 miles (see Figure 3). Add to this the fact that the vehicle dynamics (running at the TSL) and the power system (running at the SIL) are tightly coupled components of the vehicle and behave best if they are run in close proximity. This problem and its solution will be referred to as the *long haul* interface or the *RemoteLink*.

This paper describes the simulation which was designed and constructed to execute the DCE2 experiment. It then goes into depth regarding the rationale, design and implementation of the long haul interface. It then discusses the scenario which was used in the experiment. Finally, it presents some results and finishes with conclusions and future work.

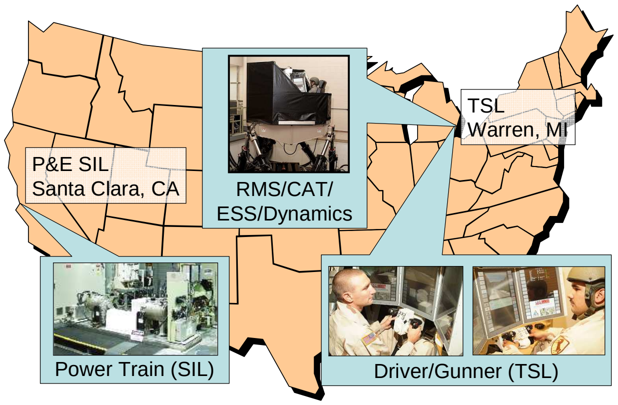

Figure 3. Geography of the assets used for the DCE2 experiment. The motion simulator and vehicle dynamics are located in Warren, MI and the CHPS-SIL is located in Santa Clara, CA.

2. Simulator Architecture and Design

2.1 Top-level design and component descriptions

The DCE2 experiment was comprised of several independent systems that were integrated to provide the functionally necessary to support two operators, each controlling a crew station cockpit on a 6-DOF motion platform in an immersive synthetic battlefield environment. The primary components of the simulation and their interrelationships are illustrated in Figure 4. In this figure the motion is provided by the ride motion simulator (RMS) on which the driver's station is mounted. The crew interface for the driver and gunner are provided by the Crew-integration and Automation Test-bed (CAT) crewstations. The simulation backbone is the Embedded Simulation System (ESS) which provides the sole interface to the CATs, the interface to OTB, the weapons model, and generates the visuals for the CAT displays. OneSAF Test Bed (OTB) was used to generate both the red and other blue forces. The Dynamics are responsible for generating own-ship vehicle motions as generated by the response to driver commands, gunner commands, traversal of the terrain, and internal or externally generated events. Such motion is then used to drive the RMS and visual channels via the ESS. The power component is a modeled representation of the SIL running locally in the GVSL. The Audio component generates the sounds in the simulation and the Stealth View component gives a trailing view (i.e. parasail view) of the own-ship in the exercise. The SIL was described in the previous section and the Long Haul component will be described in the remainder of this paper.

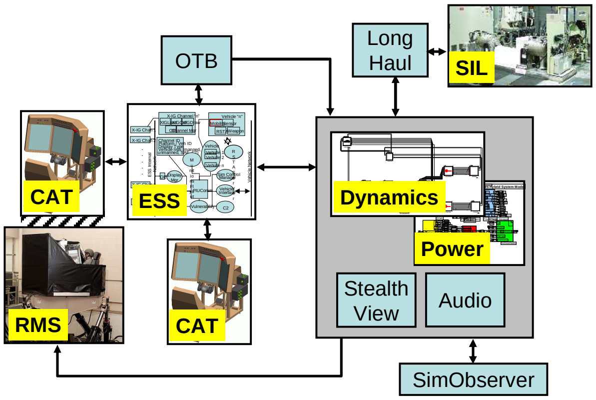

Figure 4. Schematic depiction of the DCE2 architecture which integrated the CAT crewstations and the ESS into the TSL.

The simulation in the TSL is implemented on some twenty different computers, all of which are PCs running either Windows XP® or Linux. These computers are interconnected with various 100 bps Ethernet sub-networks. The sole exception to this strategy is that the vehicle dynamics communicate with the RMS via Systran SCRAMNet® reflective memory interfaces.

Both the driver's and gunner's cockpits were implemented with the two CAT crewstations. The driver's crewstation was mounted on the RMS, while the gunner's station was stationary. The CAT crewstation is a stand-alone man-machine interface used to evaluate operational effectiveness of a two-man crew for future combat vehicles. The crew station consists of three 17 by 13 inch touch screen panels, several dedicated pushbuttons, and a steering yoke. The operator interface on the crew stations are controlled by the Soldier-Machine Interface (SMI) process which communicates with the Embedded Simulation System (ESS) over a dedicated Ethernet subnet (TCP/IP and UDP). Video is provided to the CAT by 3 Image Generator (IG) processes via a standard S-Video interface.

The vehicle dynamics model was converted from the FCS-LSI Integrated Dynamics Model (IDM) into the SimCreator® format. A hybrid power train and turret model were added. The model accepts throttle, brake, steer, and gear commands, as well as az/el rates for the turret and gun, from the ESS. It outputs vehicle state (position, orientation, and acceleration) and turret/gun position information. Additionally, the ESS provided the Non-Mobility Data Logger (NMDL) with non-mobility load information such as defensive system events. The Vehicle model also interfaces to the SIL power train hardware.

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One-SAF Testbed (OTB) generated and controlled the virtual vehicles used in this experiment (both friendly and hostile forces). It communicated with the ESS on the GVSL network using the Distributed Interactive Simulation (DIS) protocol.

2.2 SIL Description

The SIL houses a full scale combat hybrid electric power system in a highly instrumented laboratory environment. The objective power system was a series hybrid with a 250kW diesel engine/generator, two 410kW traction motors, and a 50 kW-hr battery pack connected via a 600V bus. Over 120 sensors were recorded to capture the power system's duty cycle performance. Mobility loads were imposed in the lab using bi-directional dynamometers coupled to a local real-time tracked vehicle model. Non-mobility loads were imposed on the power system using a 250kW AeroVironment AV-900 bi-directional power supply. For DCE2, the power system under test was similar to the FCS objective power system except a single traction motor was operational rather than two. To achieve realistic power system results the second traction motor was simulated in software and the associated mobility load or supply was imposed on the hardware using the AV-900.

3. Long Haul

3.1 Problem Statement

The goal of the long haul is to provide coordination and coupling between the soldier-in-the-loop simulation at the TSL and P&E SIL, while operating both in real time at a distance of 2,450 miles. This long haul integration must provide realistic driving and gunning experiences in the TSL without any abrupt, jerky motion caused by the long haul connection (i.e. it should be seamless to the driver and gunner). Second, it should provide a realistic power system response as a function of the P&E SIL's current state, meaning that the presence of the hardware affects the vehicle performance at the TSL. Likewise the long haul integration should provide meaningful power system results in the P&E SIL. Finally, both mobility and non-mobility loads generated by the driver and gunner at the TSL need to be reflected on real power system hardware.

In addition to these goals of the long haul integration, the design is subject to several constraints. The fist constraint is that both the TSL and the P&E SIL are at fixed locations separated by 2,450 miles. Second, the RMS at the TSL is a manned and therefore the long haul must not compromise its safety. Third, the long haul integration must not compromise the closed-loop stability of either the TSL's or the P&E SIL's local control loops. Fourth, there are components at both the TSL and the P&E SIL which are not readily changeable (i.e. TSL's and SIL's system latency, communication delays and reliability, SIL's speed controller, SIL hardware). Finally, the simulation design was limited by the maximum performance of the SIL hardware, which is exceeded by current FCS MGV propulsion designs.

Given these goals and constraints, a top-level diagram of the minimal information flow is shown in Figure 5. The information flow begins with the human participants who develop vehicle commands to include throttle, brake, steer, and gear from the driver and turret azimuth and gun elevation commands from the gunner. These vehicle commands flow to the power system which uses them to develop torque at the sprockets of the vehicle. These torques are then transferred to the vehicle dynamics which uses these torques along with information regarding the local terrain to solve the forward dynamics of the vehicle. As part of this solution the vehicle sprocket speeds are updated, which are then sent back to the P&E SIL. Likewise the solution of the forward dynamics is also used to develop the motion commands for the RMS and provide updated position information for the ESS visuals and weapon systems. The motion and visuals subsequently provide feedback to the driver and gunner who develop new commands to respond to what the see and feel, thus completing the loop.

The fundamental technical challenge of the long haul integration is the closed-loop coupling between the P&E SIL and the vehicle dynamics over the chosen

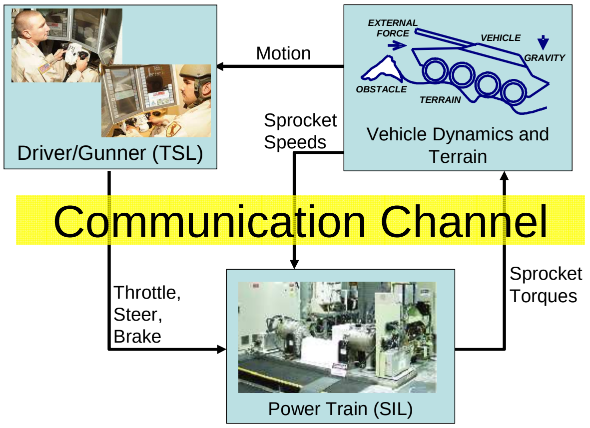

Figure 5: Long-haul topology showing information flow between the TSL and the P&E SIL over the chosen communication channel. On the top is shown components located at the TSL and on the bottom is shown the P&E SIL.

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communications channel. This is challenging in several respects. Fist, both the vehicle dynamics and the SIL are both dynamical systems in their own right. Given that they are separated by approximately 2,450 miles, there is significant delay in the communication channel; it is known that coupling two dynamical systems with delay introduces instabilities in the coupled system. The solution must therefore address the delay to assure stability. Second, the communication channel may not be reliable and may be subject to outages of varying duration. The solution must account for the expected reliability of the channel. Third, the delay of the communication channel will not be constant but will likely be subject to jitter.

3.2 Choice of Communication Channel

The first task in the design and implementation of the long haul was to evaluate different communication channels. In this regard our desire was to find a channel which experiences minimum delay and maximum reliability. In our evaluation we considered two alternatives (1) a dedicated connection over 56K bps modems and (2) a non-dedicated connection over the Internet. To evaluate these alternatives, we wrote simple software to benchmark each of the candidate communication channels. It was thought going into the evaluations that the dedicated alternative would provide superior reliability performance since it provides a continuous, dedicated point-point path, however, that turned out not to be the case. Both channels were benchmarked with packet sizes varying between 32 bytes and 1,024 bytes over the course of at least 1,000 round trips. The benchmark results were found to be largely independent of packet size and are summarized in Table 1. As can be seen, the modem solution is less reliable and experiences longer round trip times than the Internet-based solution. Given these results, we decided to use an Internet-based communication channel.

Once the Internet was chosen as the communication channel, we next had to choose the transport protocol, UDP or TCP. In our internet benchmarks, we found that both protocols exhibited the same approximate performance in terms of average delay. Of course UDP is packet-based and is therefore ‘unreliable’ and TCP is stream-based and is therefore ‘reliable’. This thinking would tend to favor TCP because of its reliability, however understanding that both protocols are layered on top of IP, which is packet-based, both suffer from the unreliable nature of IP. With UDP the risk is data loss and with TCP the risk is excessive jitter in the delay (caused by retransmission of dropped packets). In our analysis, the choice was made by comparing the transmission rate (approx. 30 ms) to the round trip time (approx. 90 ms). It is therefore clear that UDP is preferable because by the time that TCP can complete a retransmission of a dropped packet, new information would arrive. We therefore chose UDP as our transport protocol and then performed one more extensive benchmark to characterize the drop rate and jitter over the course of a normal working day. This benchmark was performed over 4.3 hours and involved the round trip measurement of 215,777 packets of which 209 were dropped for a drop rate of 0.1%. The delay times varied from 31 ms to 188 ms with the typical round trip time being 94 ms.

Table 1. Evaluation of alternative communication channels.

	Dedicated Modem	Non-dedicated Internet
Pros	Dedicated path No firewalls	Fast data rate All digital
Cons	Slow data rate Part analog	Non-dedicated path Firewalls
Round trip	350 ms	94 ms
Loss rate	1.4%	0.1%

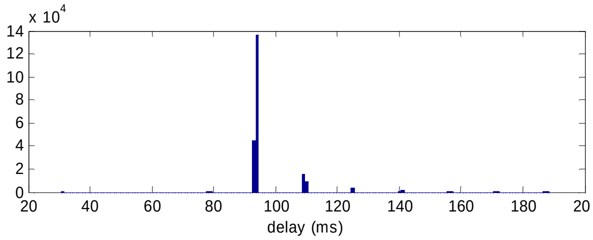

Figure 6. Histogram of round trip times for the UDP protocol with packets of 512 bytes. Histogram shows strong mode at 94 ms.

3.3 Long Haul Design

Given the network performance numbers described above, we chose to design the long haul interface to be tolerant of the loss and jitter observed. In addition we purposed to design the long haul interface so that it would be robust in the presence of markedly worse delays, jitter and loss. Finally, because the coupled system would affect the motion of the RMS and the behavior of the SIL, the system had to safe in the event of complete loss of the communication channel. So we designed it so that if the communication channel were lost, the SIL would gracefully shutdown and the GVSL would be able to continue with the experiment without the SIL. This section describes our approach to the long haul design to obtain such robustness.

In order to obtain this robustness, the logical system shown in Figure 5 was implemented as shown in

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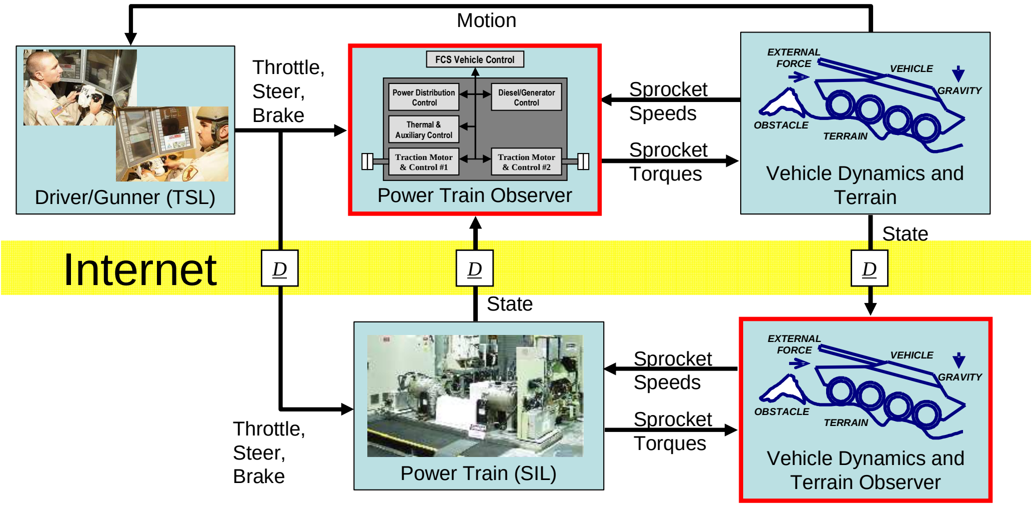


Figure 7: Long-haul topology showing driver inputs, real and modeled hybrid power systems, and two identical mobility models.

Figure 7. Observe that two components (highlighted by the red boxes) have been added, namely the Power Train Observer and the Vehicle Dynamics and Terrain Observer. In this design, the Power Train Observer serves as a proxy of the SIL so that the vehicle dynamics coupling to the power train is tight. Conversely, the Vehicle Observer serves as a proxy of the TSL vehicle dynamics so that the SIL has tight coupling between the hardware and the vehicle dynamics. At both the SIL and TSL, the power trains receive driver and gunner commands, which in turn develop sprocket torques which propel the vehicle dynamics over the terrain and likewise the vehicle dynamics provides sprocket speeds back to the power train. In effect this design implements two parallel simulations, one running at the TSL and one running at the SIL. It may now be clearly seen that in the event of a loss of the communication channel, the TSL has all that it needs to continue the simulation safely on its own. The SIL on the other hand would not have driver/gunner commands available and would therefore shut down in such an event.

Because the design incorporates two parallel simulations and because the Power Train Observer does not exactly represent the SIL hardware, the two simulated vehicles will drift apart in their states over time. This phenomenon is illustrated in Figure 8. It is particularly important that the SIL vehicle position be consistent with that in the TSL (e.g. when traversing a bridge). In order to maintain consistency between states which are deemed important both the Power Train Observer and Vehicle Observer were designed to track the states of the P&E SIL and TSL vehicle respectively. The techniques used to implement this tracking are referred to as *State Convergence* (SC) in the remainder of the paper.

3.4 State Convergence

The design had identical mobility models operating in real time at both locations with a state convergence control scheme [3] to keep both models coordinated in real time. To ensure soldier and hardware safety during the experiments, hardware status signals at both locations were coupled to their respective safety shutdown triggers. This provided automated fault detection and shutdown capability.

Two coupled control systems provide mobility state convergence at the P&E SIL and power system state convergence at the TSL. Both control systems are designed in an observer-oriented controls framework to coordinate states in the two locations despite power

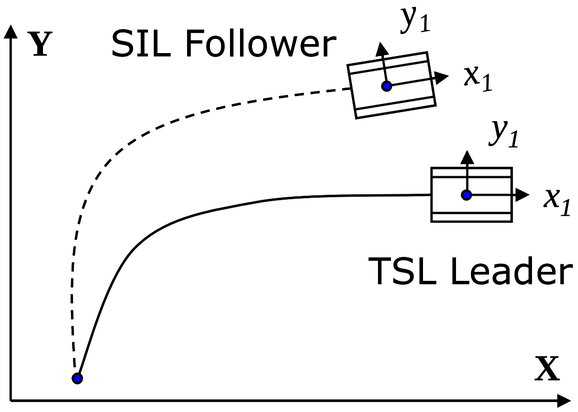


Figure 8: Mobility state convergence keeps both vehicle models coordinated in real time

system model differences and long distance communication delays.

Mobility state convergence provides inputs to the P&E SIL's vehicle dynamics model to ensure the position and velocity track the TSL's mobility model in real time (Figure 8). The P&E SIL model represents the observer and the TSL's model represents the truth, or reference.

Both augmented throttle inputs and skyhook forces and moments are computed based on position and velocity errors between the two mobility models. These inputs are used with the P&E SIL vehicle model because the TSL's mobility model drives the soldier's motion base. The TSL's mobility model is qualified for a manned operation rating and cannot be modified.

Power system state convergence provides inputs to the modeled hybrid power system, CHPSPerf, operating in the TSL. CHPSPerf nominally provides torques to the TSL mobility model as a function of driver inputs and power system states. In addition, CHPSPerf also accepts inputs from power system state convergence that causes the modeled bus voltage to track real bus voltage at the P&E SIL. CHPSPerf is the observer to the P&E SIL's hardware reference. Bus voltage tracking provides realism to the experiment by including the influence of real power system hardware.

As a result, variations and limitations in the P&E SIL's power system can influence how the driver and gunner operate the simulated vehicle. This real-time coupling between vehicle operation and real hardware power system response is a distinguishing feature which separates the DCE2 experiment from DCE1 and other record-and-playback approaches.

3.4.1 Power System Model for State Convergence

The power system state convergence is an observer-based design shown in Figure 9. It uses the power system model for forward dynamics and incorporates a correction based on state errors. The power system model is responsible for modeling the MGV's hybrid-electric power system at the TSL. It models power generation, storage, conversion and management systems. It receives commands from the driver and gunner and provides torques to the vehicle dynamics model. The power system is implemented in Simulink® as a library of standardized interconnected power system components. This toolset is called CHPSPerf. The power system is a series hybrid-electric power system and uses a diesel engine coupled to an induction motor/generator unit (Prime Power in Figure 10) to provide continuous electrical power through an inverter to an unregulated high-voltage DC bus. A battery pack (Energy Storage in Figure 10) sized to provide silent watch and silent mobility functions is attached directly to the bus and maintains bus voltage at approximately 600 Volts. Attached to the high voltage bus are two independent induction motors for the left and right sprocket drives (Traction Drive Motors) capable of providing 410 kW of continuous power and over 900 kW of burst power for

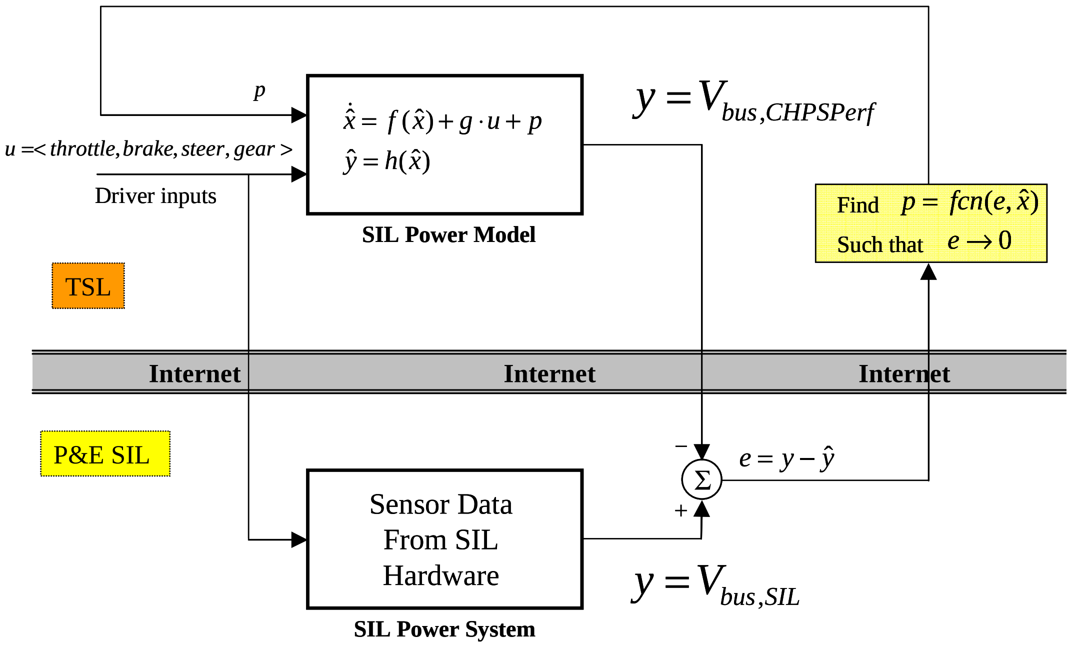


Figure 9: Power system state convergence control system diagram.

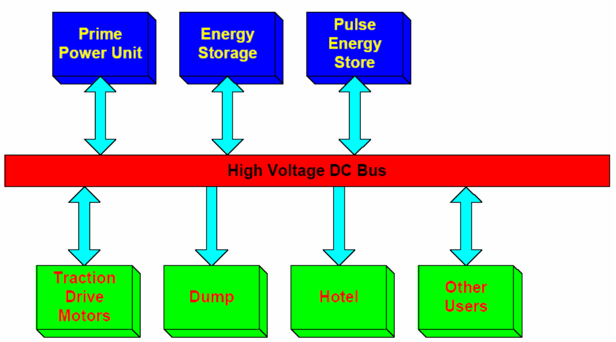


Figure 10: Layout and components of the series hybrid power system

braking and acceleration functions. A brake or dump resistor is also attached to the bus to protect it from over-voltage conditions that might arise due to heavy braking or long duration regeneration events.

Motor/Generator – The power system uses induction machines for the traction motors, generator and cooling fan. The traction motors and the generators in the simulation are 3-phase induction machines. Because of the relative importance of the mobility system in the overall power system efficiency (accounting for upwards of 90 percent of the total energy consumption during a typical mission) a substantial amount of effort has been expended in developing reliable and accurate machine models for this aspect of the system.

Battery – The battery in the simulation is based on the Li-Ion cell model proposed by SAFT. In this model, the battery is represented by a capacitor/resistor network. The single cell model was subsequently modified to account for multiple series/parallel combinations of cells.

Engine – The engine model is based on a simple table lookup of the torque and fuel consumption properties and therefore includes no dynamics. Both the torque and specific fuel consumption tables are two-dimensional which are indexed by throttle position and engine speed.

Dump Resistor – The dump resistor is modeled as a resistor with a resistance that varies from zero to its maximum value with a linear gain.

Thermal Management – The thermal management system is a set of components which can be linked together to form a closed- or open-loop thermal control and management system. The major components include the tank, the heat exchanger and the fan. The tank is a constant volume system implemented as time-dependent mass and energy equations which are solved for the tank fluid and exit fluid temperatures. The heat exchanger model uses a fixed effectiveness to calculate the thermal performance given the inlet properties for the two fluids including their density, viscosity, thermal conductivity and specific heats. Finally the fan computes the load on its induction motor using the pressure drop properties of the radiator and system ductwork. A controller varies its speed based on cooling fluid temperatures.

Converter – The DC/AC converter model is based on the losses of both passive component (capacitor) and active switching components. The passive losses are computed using the equivalent series resistance of the capacitor while the active losses are determined by the diode and switch losses during turn-on, turn-off and steady-state standoff.

3.4.2 Vehicle Dynamics Model for State Convergence

The vehicle state convergence is also an observer-based design shown in Figure 11. It uses the vehicle dynamics model for forward dynamics and incorporates a correction based on state errors. The vehicle mobility model is responsible for the computation of the vehicle's position, velocity, and acceleration as influenced by the power system and the terrain. It generates the commands for the motion base simulator and updates vehicle global position for the ESS. In its implementation, the vehicle dynamics encapsulates both the terrain model and the power system model. Because the vehicle dynamics model feeds motion commands to the RMS it must model the tracks, suspension, and terrain to a high degree of fidelity. As such it was implemented in a real-time dynamics code called SimCreator's® multi-body dynamics component library [3], [4].

SimCreator® is a commercial product that provides a graphical hierarchical control system simulation and modeling environment. The suspension and track geometry was chosen from an existing vehicle for which each track has six road arms and wheels, a front drive sprocket and a rear idler. A continuous track is wrapped around the wheels and the supporting sprocket and idler. Each road arm and wheel includes a torsion bar for the suspension. To make the dynamics similar to a mounted combat system (MCS), the inertia properties of the chassis were changed so that the gross vehicle weight is 24 tons. Ground forces that support and propel the vehicle are transferred through the track to the sprockets and road wheels. McCullough and Haug [2] developed a track vehicle model that calculates forces from both track and ground using the kinematic state of the vehicle and applies these forces

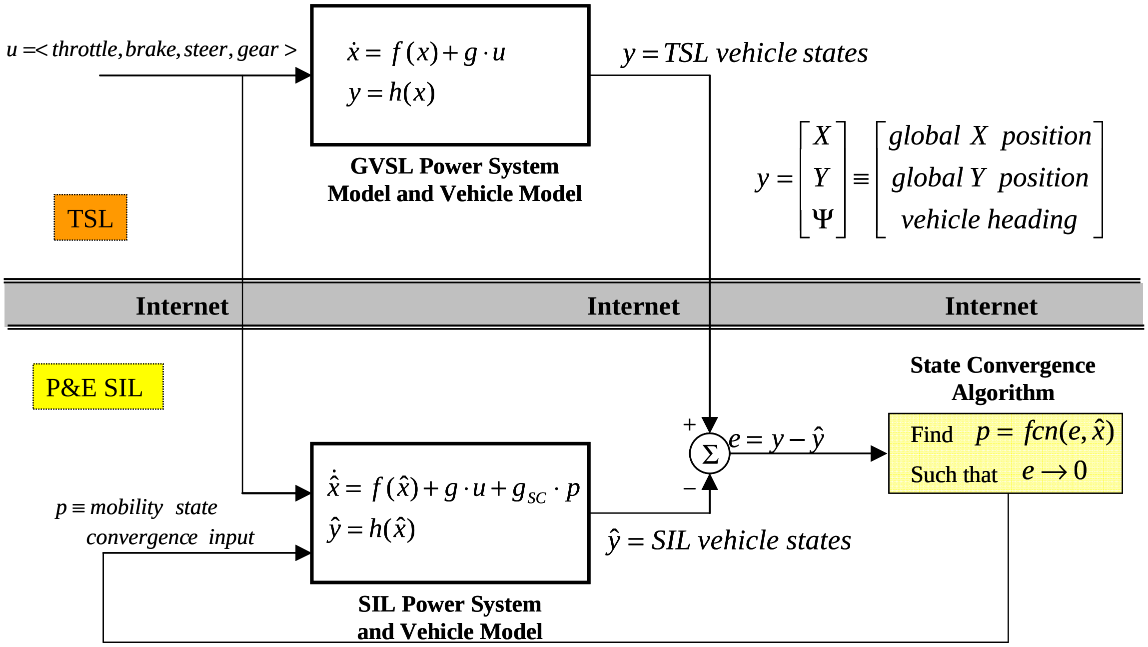


Figure 11: Mobility state convergence control system diagram.

through the wheel, sprocket, and idler centers. The SimCreator® track model used for the experiment also transfers the track/ground interface forces to the chassis in a similar manner. The track-terrain interface includes a soil model based on the work of Bekker as reported in Wong [6].

3.4.3 Long Haul Implementation

The long haul is implemented with a series of intricate connections between processes running on computers and hardware measurements. With respect to the P&E SIL, two computers are the central components to the operation of the P&E SIL. The first computer is the CHPS computer (see Figure 12), which runs the QNX hard real-time operating system.

This computer contains a controller that controls the behavior and performance of all of the components of the series hybrid power system hardware in the P&E SIL. The other P&E SIL computer is the VMS computer, which runs the vehicle model, contains the state convergence algorithms, and interfaces with the bi-directional UDP communications to and from the TSL. In the figure, the blue arrows indicate all of the inputs and outputs going to the VMS computer, while the red arrows indicate all of the inputs and outputs going to the CHPS computer. Information is passed between the VMS and CHPS computers via a PCI bus at the rate of 100 Hz.

Notice the bottom-left portion of the figure corresponding to the "Crewstation GUI" title. The function of this portion of the long haul is to provide driver inputs to the P&E SIL and receive vehicle motion feedback. This portion of the long haul can either be local to the P&E SIL or can be located remotely. In the case of the long haul, the driver is located across the country at the TSL in Warren, MI.

Examining the bottom right corner of Figure 12 reveals the P&E SIL Test Manager. This item is an interface that governs the operation of the P&E SIL. This interface controls the startup, shutdown, operation, and monitoring of all of the components in the P&E SIL. The Test Manager communicates directly with the CHPS computer, which in turn communicates with the P&E SIL hardware. The P&E SIL must be running in a stable and fault-free manner before the long-haul connection with the TSL is established.

The code that runs on the VMS and CHPS computers is derived from the long haul design. The code for the vehicle model, CHPS Controller, and State Convergence is constructed in Matlab/Simulink. In order to transform the Matlab/Simulink code to become real-time executable code, it is exported through Real Time Workshop. This code runs on both VMS Linux machine and the CHPS QNX machine. This process to generate the implemented real-time code is illustrated in Figure 13.

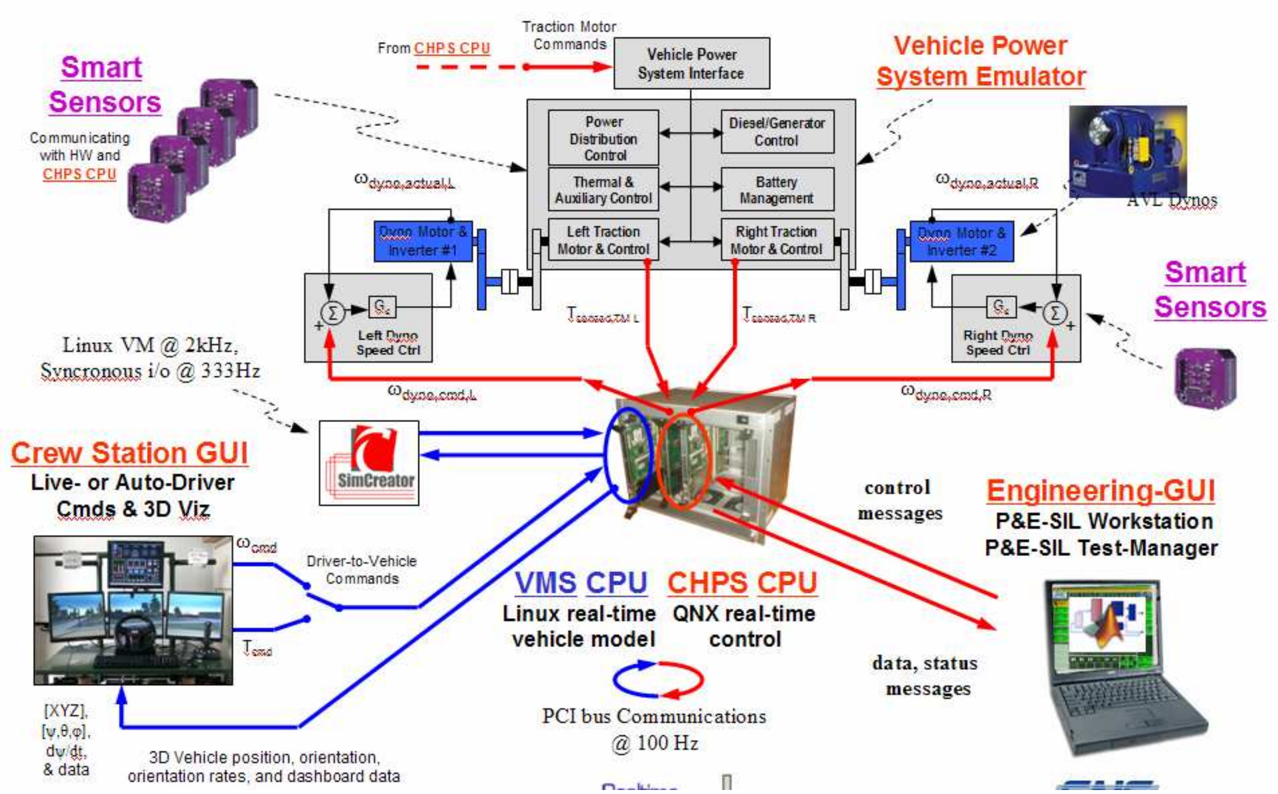


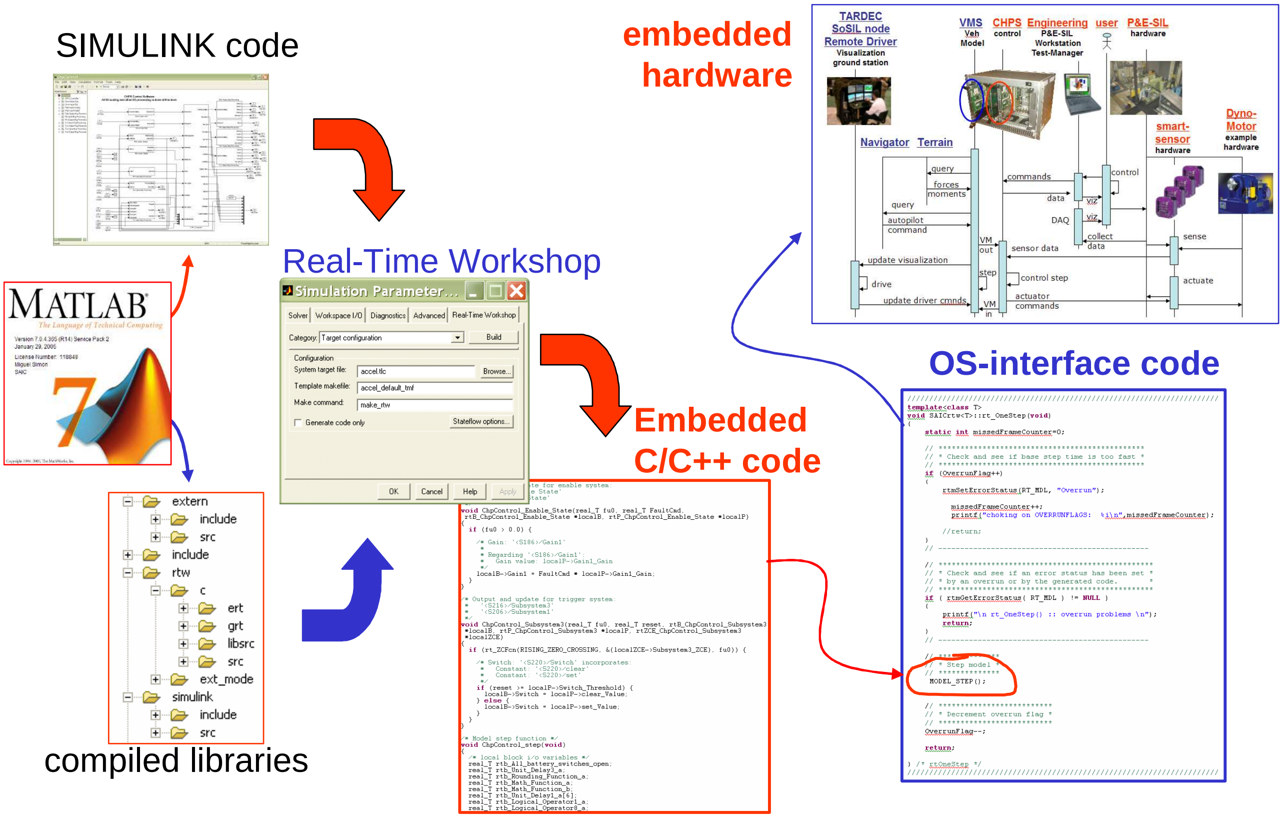
Figure 12: P&E SIL hardware and software layout.

The last important step in the implementation of the long haul is the safety issue. With respect to the safety and protection of the P&E SIL hardware, a series of status signals is included in the data-stream going from the TSL to the P&E SIL. These signals indicate the on/off state of the TSL vehicle dynamics model, the TSL power system model, the ESS, and whether or not the round-trip delay is less than 10 seconds. If any of these signals are in the off or false states, the P&E SIL enters a shutdown mode. In addition, a human operator is present at the P&E SIL and has the ability to manually shut down the P&E SIL. With respect to the protection of the soldiers in the TSL, a series of fault signals from the P&E SIL data-stream is monitored. If any vehicle dynamics faults, hardware faults, or state convergence faults are present, the feedback from the P&E SIL hardware is shut off to the power system state convergence section, the experiment continues in an open loop mode.

4. Experiment Design

The experiment was designed to measure the duty cycle of the MCS vehicle given the scenario. Each experimental run incorporated three humans (2 subjects and one experimenter). The experiment was designed to evaluate the duty cycle over twelve teams each consisting of a driver and a gunner. A total of twelve soldiers were used to compose these teams and these soldiers participated in the experiment in groups of four per week. At the beginning of their respective week, each soldier was assigned a subject number and also assigned a partner (partially determined based on their working together in their normal duties). Each pair of soldiers would then execute the experiment twice, once as the gunner and once as the driver. Each different configuration was additionally assigned a team number, which corresponded with the subject number of the soldier who was driving. This numbering scheme is summarized in Table 2.

To assist the vehicle crew (driver & gunner) negotiate the scenario, a third soldier was employed as an experimenter called the “Proxy Commander”. This soldier was from the same organization and served as the ranking NCO while the soldiers were at the TSL. His responsibility as an experimenter was to serve as the notional commander of the vehicle. In this role he would relay orders and reports from notional higher commands and give the crew specific instructions with regard to tactics and engagements. The particular soldier who served in this capacity is an E7 Platoon Sergeant with 18 years of experience.



Category: Target configuration

Configuration

System target file: accel.tlc

Template makefile: accel_default_tmf

Make command: make_rtw

☐ Generate code only

```
te for enable system:
e State'
State'
void ChpControl_Enable_State(real_T fu0, real_T FaultCmd,
 rtB_ChpControl_Enable_State *localB, rtP_ChpControl_Enable_State *localP)
{
  if (fu0 > 0.0) {

    /* Gain: '<S186>/Gain1'
     *
     * Regarding '<S186>/Gain1':
     *   Gain value: localP->Gain1_Gain
     */
    localB->Gain1 = FaultCmd * localP->Gain1_Gain;
  }
}

/* Output and update for trigger system:
 *   '<S216>/Subsystem3'
 *   '<S206>/Subsystem1'
 */
void ChpControl_Subsystem3(real_T fu0, real_T reset, rtB_ChpControl_Subsystem3
 *localB, rtP_ChpControl_Subsystem3 *localP, rtZCE_ChpControl_Subsystem3
 *localZCE)
{
  if (rt_ZCFcn(RISING_ZERO_CROSSING, &(localZCE->Subsystem3_ZCE), fu0)) {

    /* Switch: '<S220>/Switch' incorporates:
     *   Constant: '<S220>/clear'
     *   Constant: '<S220>/set'
     */
    if (reset >= localP->Switch_Threshold) {
      localB->Switch = localP->clear_Value;
    } else {
      localB->Switch = localP->set_Value;
    }
  }
}

/* Model step function */
void ChpControl_step(void)
{
  /* local block i/o variables */
  real_T rtb_All_battery_switches_open;
  real_T rtb_Unit_Delay3_a;
  real_T rtb_Rounding_Function_a;
  real_T rtb_Math_Function_a;
  real_T rtb_Math_Function_b;
  real_T rtb_Unit_Delay1_a[6];
  real_T rtb_Logical_Operator1_a;
  real_T rtb_Logical_Operator8_a;
```

```
/////////////////////////////////////////////////////////////////////////
template<class T>
void SAICrtw<T>::rt_OneStep(void)
{
    static int missedFrameCounter=0;

    // ***********************************************
    // * Check and see if base step time is too fast *
    // ***********************************************
    if (OverrunFlag++)
    {
        rtmSetErrorStatus(RT_MDL, "Overrun");

          missedFrameCounter++;
          printf("choking on OVERRUNFLAGS:  %i\n",missedFrameCounter);

        //return;
    }
    // ------------------------------------------------

    // *************************************************
    // * Check and see if an error status has been set *
    // * by an overrun or by the generated code.       *
    // *************************************************
    if ( rtmGetErrorStatus( RT_MDL ) != NULL )
    {
        printf("\n rt_OneStep() :: overrun problems \n");
        return;
    }
    // ------------------------------------------------

    // **************
    // * Step model *
    // **************
     MODEL_STEP();

    // *************************
    // * Decrement overrun flag *
    // *************************
    OverrunFlag--;

    return;

} /* rtOneStep */
/////////////////////////////////////////////////////////////////////////
```

Figure 13: P&E SIL hardware and software layout.

Table 2. Layout of the team and subject numbers.

	Team	Driver	Gunner	Scenario
Week 1	T01	S01	S02	A
	T02	S02	S01	B
	T03	S03	S04	A
Jun 19-22	T04	S04	S03	B
Week 2	T05	S05	S06	A
	T06	S06	S05	B
	T07	S07	S08	A
Jun 26-29	T08	S08	S07	B
Week 3	T09	S09	S10	A
	T10	S10	S09	B
	T11	S11	S12	A
Jul 10-13	T12	S12	S11	B

4.1 Scenario Description

To measure a proper duty cycle, the choice of scenario was very important. In the design of the experiment, the TSL engineers wanted a scenario which stressed the system and yet was militarily relevant and the Unit of Action Maneuver Battle Laboratory (UAMBL) at Ft. Knox, KY agreed to develop a scenario. The TSL wrote a document describing the desirable aspects of a scenario, i.e. that it contain particular events such as hill climbing, main gun use, defensive system use, etc. UAMBL recommended the Ft. Knox terrain for the DCE2 experiment because it is CONUS and it contains the grade features necessary to stress the power system.

The scenario delivered by UAMBL provided two levels of detail. The highest level is called the “wrap around” scenario which describes what the FCS UA, battalion, and companies are doing in the notional operation. In it the FCS-UA must cross the Ohio River. On the other hand, the low-level “specific” scenario defined the role of one platoon to support this action. This platoon must move from their present position to a support by fire position to aid the crossing. This specific scenario is what was implemented in the simulation environment.

The scenario as implemented by the TSL is depicted graphically in Figure 14. It essentially consists of two phases, the first being a road march from SP to RP along Route Black and the second being a tactical maneuver from RP to set the support by fire position SBF3. The length of whole route from the SP to the SBF3 is approximately 13 km and typically took approximately 35 to 40 min to complete.

Along Route Black red dismount forces were placed in ambush positions. These dismounts were placed in

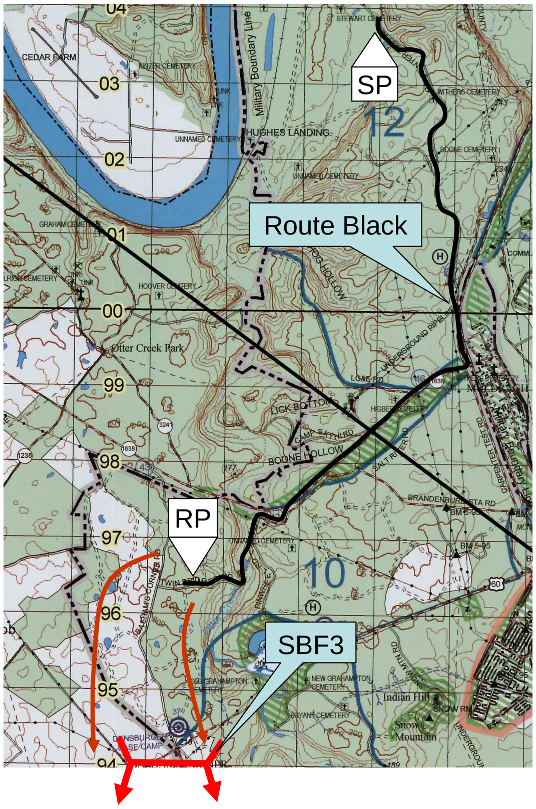


Figure 14. Graphics depicting the Fort Knox experiment scenario.

teams of three and were equipped with RPGs. In total there were nine areas along Route Black in which these RPG teams could be placed within range of the passing convoy. In the open area between the RP and SBF3 a platoon of BMPs were placed and a platoon of T-80s were placed. The platoon had several opportunities to engage these vehicles all of which were line-of-sight (LOS) engagements.

4.2 OTB Implementation

The scenario as described above was implemented in OneSAF Test Bed (OTB) v2.5. The balance of the MCS platoon was implemented in OTB and all of the red forces were implemented in OTB. The terrain on which the OTB was run was a CTDB version of the Ft. Knox database.

4.2.1 Blue Force Implementation

The blue MCS platoon was implemented as shown in Figure 15. The lead vehicle in the platoon is the simulated vehicle (i.e. ownship) while the remaining three vehicles are simulated by OTB. By placing the simulated vehicle in the front of the platoon, the driver is freer to act independently.

The blue vehicles were initialized to begin in column formation behind the simulated vehicle. Once the experiment began they were set to “follow simulator” mode. They then were free to engage the red forces as their algorithms directed.

4.2.2 Red Force Implementation

Red forces were implemented in two different scenarios labeled “A” and “B”. In each of these scenarios, the MCS platoon participated in seven engagements with different red forces. Five of these engagements were against RPG teams, one engagement was against a platoon of BMPs and one engagement was against a platoon of T-80s. The MCS platoon encountered the five RPG teams first. They then encountered the BMP platoon and finally encountered the T-80s. In this sequence of engagements, the first four were unique to the particular scenario (i.e. A or B) and the last three were the same for both scenarios. The break down of the engagements is shown in Table 3. The sequence of these engagements is shown in Figure 16.

The RPG engagements were implemented with five teams consisting of three dismounted enemy soldiers each. An example RPG engagement is shown in Figure 17 where the road is shown in red, the area of contact is shown as a yellow line, the RPG dismounts are highlighted with yellow circles and the direction of travel is shown as a yellow arrow. In this figure the relative positioning, range and spacing of the dismounts is typical. The dismounts were intentionally placed in the normal scanning arc of the gunner which was approximately ± 30°. This was done because it was understood that the second and third vehicles in

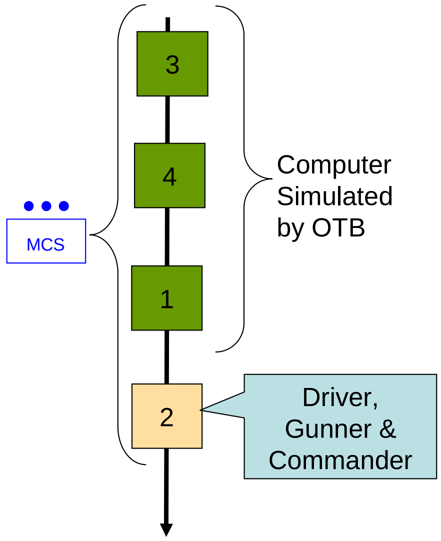


Figure 15. MCS Platoon Vehicle Ordering.

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the column were responsible for flank security. In each case the RPG dismounts were stationary and did not move during the simulation.

The BMP engagement was designed to occur at the SP and occurs at close range. The T-80 engagement occurred at two different points in the scenario, one engagement was far and one was close. The far engagements occurred while the MCS vehicle was still on route black. The first sight was sometimes at a distance out of range for a LOS engagement. The MCS gunner typically got a second view of the T-80s while on route black at just under the maximum range of his LOS weapon. Although the MCS crews did not always do so, many of them took a shot at each of the T-80s from this stand off range. After this long-distance engagement, the MCS vehicle would then finish route black completing (perhaps) engagements A/B-4, A/B-5. After passing the RP of route black, the MCS vehicle would finish engagement A/B-6 and then engage the T-80s at short distances. Once they had completed engagement A/B-7 the only remaining task for the MCS crew was to set the SBF position.

Table 3. Engagement labels for scenarios A and B

Engagement	Scenario A	Scenario B
#1	A-1	B-1
#2	A-2	B-2
#3	A-3	B-3
#4	A-4	B-4
#5	A-5	B-5
#6	A-6	B-6
#7	A-7	B-7

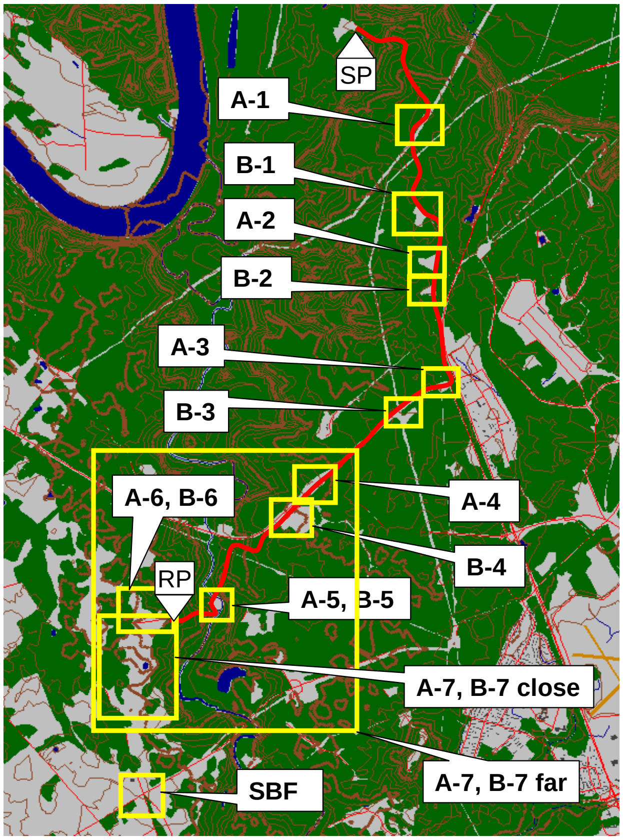

Figure 16. Positioning of the seven engagements encountered by the platoon in the scenario.

5. Experiment Results

5.1 Subject demographics

The soldiers who participated in the DCE2 were twelve males from the 11th Armored Cavalry Regiment stationed at the National Training Center, Ft. Irwin, CA. Each soldier's current MOS is 19K (M1 Armor Crewman) with the average time in this MOS of 6.33 years. The soldiers had an average length of service of 6.75 years and had ages ranging from 20 to 34 years with an average of 26.8 years. Their ranks were distributed as follows, one E4, six E5s, and five E6s.

6. Measured Duty Cycles

Of the twelve teams which performed the experiments, ten of them ran to completion, the other two had to be aborted mid-way through and had to be resumed at the point where the simulation stopped. Of the twelve runs, the P&E SIL began running with the TSL on six of them. For four of these runs the SIL and/or TSL had to abort the run due to a technical difficulty, two of the runs saw the TSL and SIL run to completion. In these two runs, the long haul solution was shown to be robust

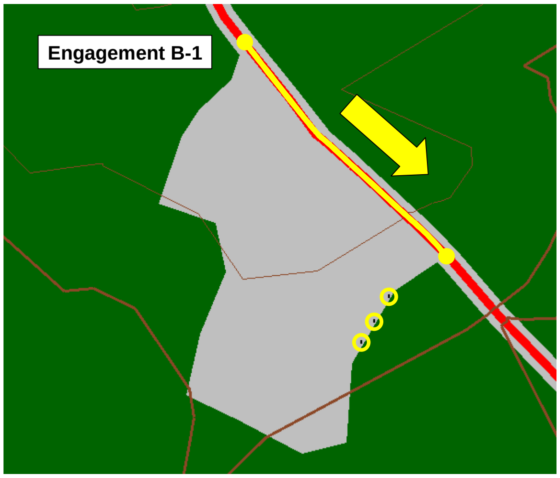

Figure 17 Example of red dismount positions for a typical dismount engagement.

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in the presence of variable propagation delays. In practice the actual round trip delay was measured to be approximately 800 ms and during one run the Internet communications experienced an outage of 7 seconds and gracefully recovered. A plot showing the round trip delay characteristic is shown in Figure 18. For this same run, the performance of the vehicle state convergence is shown in Figure 19.

Regarding the actual duty cycles recorded by the TSL, all pertinent vehicle and power system data were recorded for each run and archived for further use and analysis. All crew behaviors were recorded to include instantaneous driver and gunner commands. For those runs with which the SIL ran, time-correlated SIL data were recorded. For non-mobility loads all of the fire and detonation events for both the red and blue forces were logged.

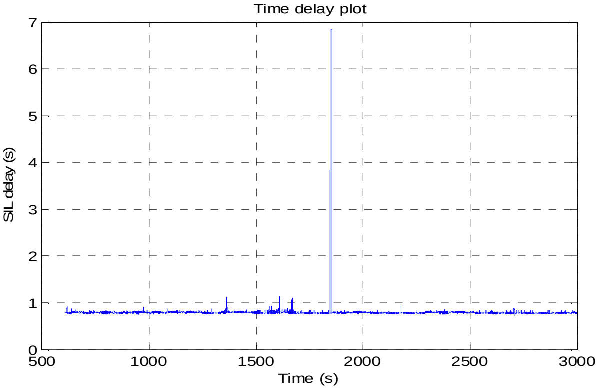

Figure 18. Plot of round trip delay between TSL and the SIL. Note that the state convergence solution recovered from the 7 second outage.

As an example of the types of data that were recorded, Figure 20 shows the paths of all twelve teams through the whole scenario. Observe that there is consistency while the vehicles are on route black. After the operators reach the SP, they were free to maneuver tactically to engage the BMPs and T-80s, causing the large variation observed in the lower-left corner of the figure. Figure 21 shows a close-up of the paths taken in the tactical maneuver portion of the scenario.

The definition of a duty cycle also includes the events and circumstances associated with each point on the path driven. Because each team negotiated the course at different speeds, plots with time as the independent variable introduce skew among events. For this reason some of the following plots are shown as functions of distance along the course. First we examine the terrain

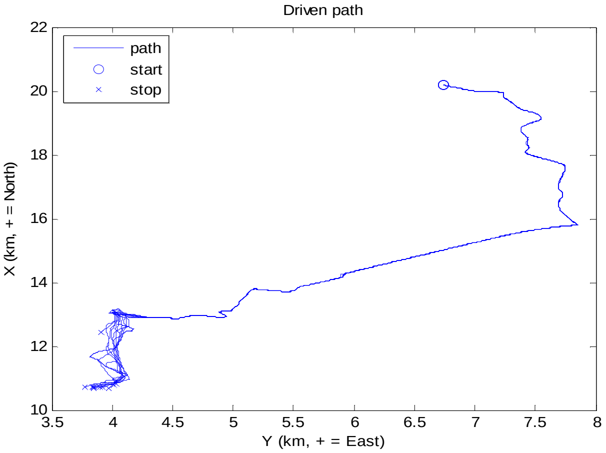

Figure 20. Overlaid path of all twelve experiment runs over all 13 km of the scenario.

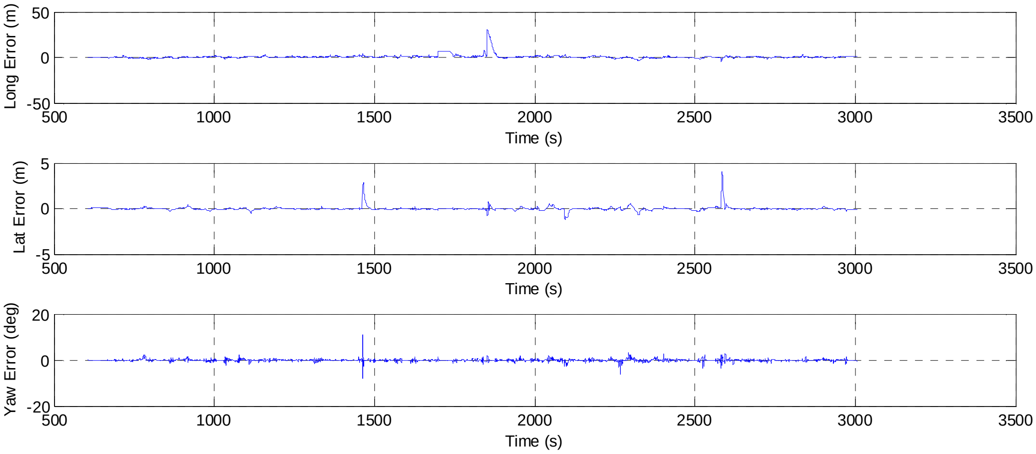

Figure 19. Plots depicting the performance of the vehicle state convergence. Shown are the longitudinal error (top), the lateral error (middle) and the yaw error (bottom). Note that the network outage at approx 1,700 seconds caused a substantial error in the longitudinal position, however, when communications resumed, the state convergence closed the error and maintained its prior performance.

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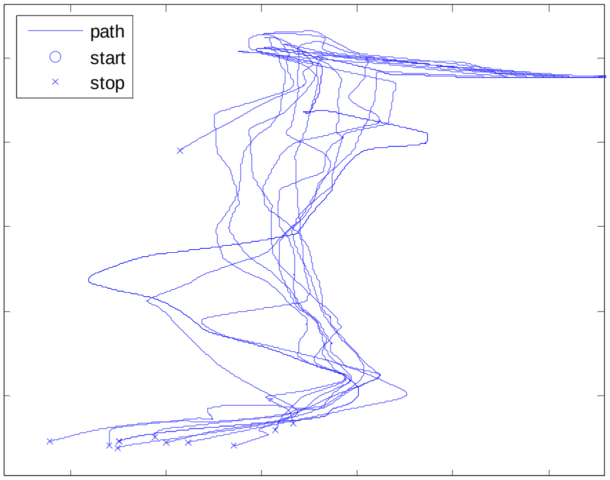

Figure 21. Close-up of overlaid paths during the tactical maneuver portion of the scenario. Note that one run was terminated early.

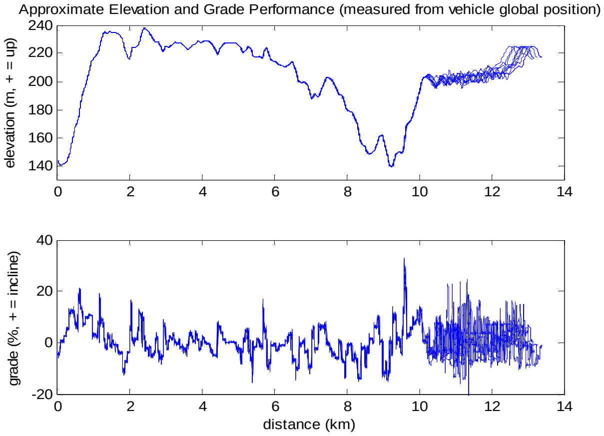

Figure 22. Over laid plot of the terrain for all twelve runs as a function of distance. Included are the elevation (top) and grade (bottom).

features along the route as shown in Figure 22. There we observe the rich variety of elevation and grades encountered by the vehicle along the route. Also included in the definition of a duty cycle are the behaviors of the crew along the route. First we observe the longitudinal commands of the driver in Figure 23 and of the lateral performance of the driver in Figure 24. Next, the duty cycle definition may also include the activity of particular vehicle components as illustrated with the battery in Figure 25 and the turret and gun as illustrated in Figure 26.

7. Conclusion

In this paper we have presented an approach to integrating two Army laboratories in a real-time hardware/man-in-the-loop experiment. We discussed the unique challenges in developing such a simulation and presented our approach to solving them using the observer-based state convergence approach. We discussed the design and execution of the experiment and have presented results with respect to the performance of the long-haul solution. Finally, we have presented some data which are representative of the types of results measured in the DCE2.

8. References

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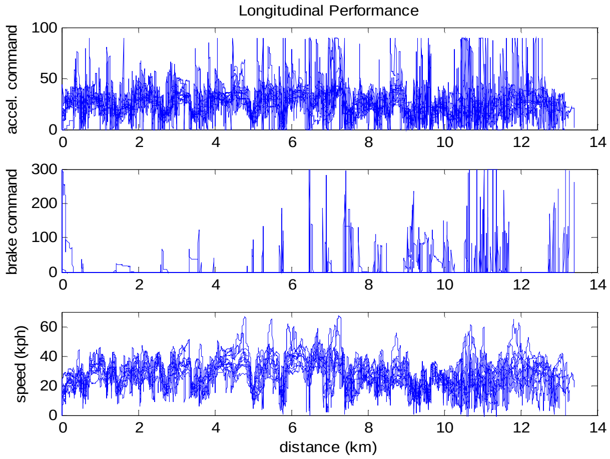

Figure 23. Over laid plot of the longitudinal performance for all twelve runs as a function of distance. Included are the throttle (top), the brake (middle) and speed (bottom).

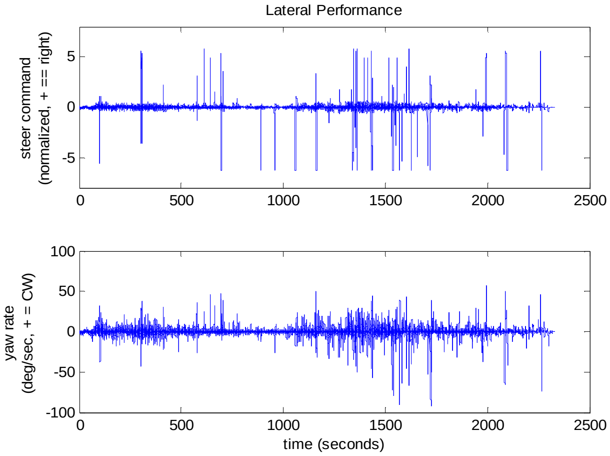

Figure 24. Over laid plot of the lateral performance for all twelve runs as a function of distance. Included are the steer (top) and yaw rate (bottom).

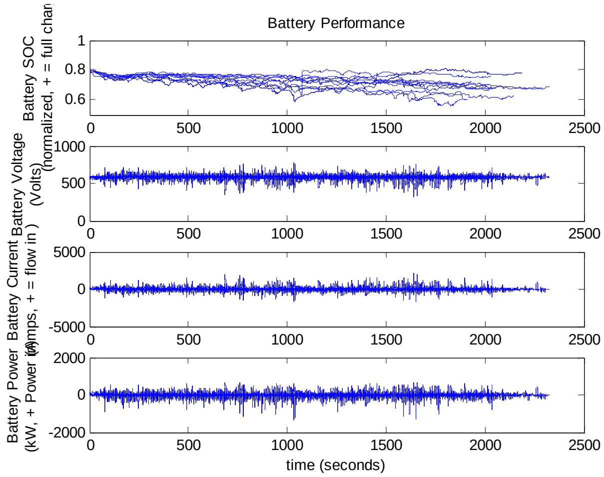

Figure 25. Over laid plot of the battery performance for all twelve runs as a function of time. Included are the state of charge (top), the voltage (middle top), the current (middle bottom) and the power (bottom).

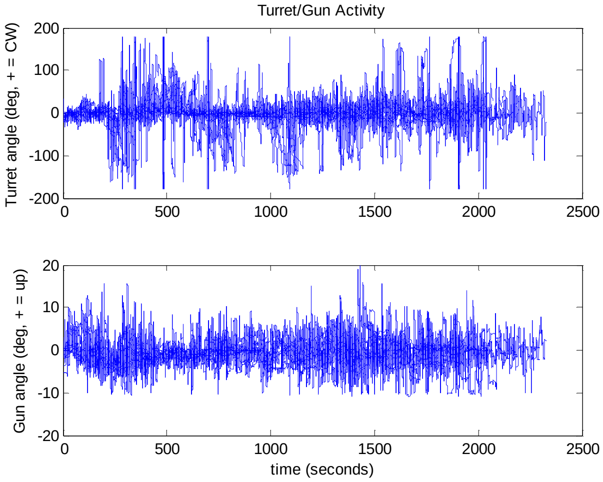

Figure 26. Over laid plot of the turret and gun activity for all twelve runs as a function of time. Included are the turret angle (top) and the gun angle (bottom).

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