16688

2006-01-3077

Robust Control Techniques Enabling Duty Cycle Experiments Utilizing a 6-DOF Crewstation Motion Base, a Full Scale Combat Hybrid Electric Power System, and Long Distance Internet Communications

Marc Compere, Jarrett Goodell, Miguel Simon, Wilford Smith
Science Applications International Corporation

Mark Brudnak
U.S. Army TARDEC

ABSTRACT

The *RemoteLink* effort supports the U.S. Army's objective for developing and fielding next generation hybrid-electric combat vehicles. It is a distributed soldier-in-the-loop and hardware-in-the-loop environment with a 6-DOF motion base for operator realism, a full-scale combat hybrid electric power system, and an operational context provided by OneSAF. The driver/gunner crewstations rest on one of two 6-DOF motion bases at the U.S. Army TARDEC Simulation Laboratory (TSL). The hybrid power system is located 2,450 miles away at the TARDEC Power and Energy System Integration Laboratory (P&E SIL). The primary technical challenge in the *RemoteLink* is to operate both laboratories together in real time, coupled over the Internet, to generate a realistic power system duty cycle.

A topology has been chosen such that the laboratories have real hardware interacting with simulated components at both locations to guarantee local closed loop stability. This layout is robust to Internet communication failures and ensures the long distance network delay does not enter the local feedback loops. The TSL states and P&E SIL states will diverge due to (1) significant communications delays and (2) unavoidable differences between the TSL's power-system simulation and the P&E SIL's real hardware-in-the-loop power system. Tightly coupled, bi-directional interactions exist among the various distributed simulations and software- and hardware-in-the-loop components representing the driver, gunner, vehicle, and power system. These interactions necessitate additional adjustment to ensure that the respective states at the TSL and P&E SIL sites converge. This is called *state convergence* and ensures the dominant energetic states of both laboratories remain closely matched in real time. State convergence must be performed at both locations to achieve bi-directional, real-time interaction like that found on a real vehicle. The result is a distributed control system architecture with Internet communications in the state convergence feedback loop.

The Internet communication channel is a primary source of uncertainty that impacts the overall state convergence performance and stability. Multiple control schemes were developed and tested in simulation. This paper presents robust control techniques that compensate for asynchronous Internet communication delays during closed loop operation of the TSL and P&E SIL sites. The subsequent soldier- and hardware-in-the-loop experiments were performed using a combination of nonlinear Sliding-mode and linear PID control laws to achieve state convergence at both locations. The control system development, performance, and duty cycle results are presented in this paper.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **10 NOV 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Robust Control Techniques Enabling Duty Cycle Experiments Utilizing a 6-DOF Crewstation Motion Base, a Full Scale Combat Hybrid Electric Power System, and Long Distance Internet Communication**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Marc Compere; Jarrett Goodell; Miguel Simon; Wilfor Smith; Mark Brudnak**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **SAIC 8303 N. MoPac Expy. Suite B-45 Austin, TX 48759, USE US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000**	10. SPONSOR/MONITOR’S ACRONYM(S) **TACOM/TARDEC** 11. SPONSOR/MONITOR’S REPORT NUMBER(S) **16688**

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

13. SUPPLEMENTARY NOTES
Presented at SAE Power Systems Conference, November 2006, New Orleans, LA, USA, Session: Advanced Power Systems Technologies

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**10**	

Introduction

A series of Duty Cycle Experiments (DCE) have used the growing fidelity of TARDEC's Power Budget Model and *RemoteLink* technology to gain increasingly useful duty cycles for designing the Army's Future Combat System (FCS) family of vehicles. Duty Cycle Experiments 1.0 and 1.1 were simulation-based experiments with real time soldier-in-the-loop inputs and physics-based models [1,2]. This paper presents the *RemoteLink* control system developed for Duty Cycle Experiments 2.0 and 2.1. The 2.x experiments extend the 1.x experiments and incorporate a full scale combat hybrid electric power system at TARDEC's Power and Energy System Integration Laboratory (P&E SIL) in San Jose California. A standard Internet connection was used to connect the two laboratories in real-time coordinated experiments 2,450 miles apart (Figure 1).

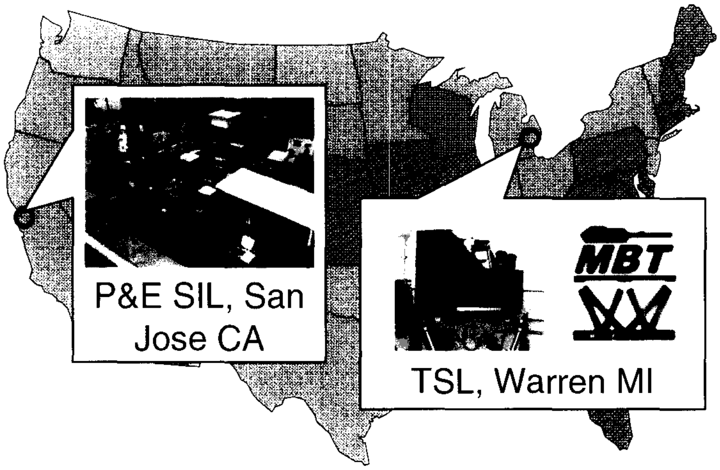


Figure 1: TARDEC Power and Energy Lab and TARDEC Simulation Lab

The goal of Duty Cycle Experiment 2.x was to capture operational duty cycles using Army soldiers in a realistic virtual environment with appropriate visual, sound, and motion cues while interacting with a full-scale combat hybrid electric power system. 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 along the course 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. Within the scenario, the duty cycle inputs result in a use-history specific to that particular vehicle design and component choice. The use-history outputs may then be used to compute the vehicle's performance and cost metrics associated with the duty cycle.

System and Experiment Description

The Warren, Michigan based TARDEC Simulation Lab (TSL) assets include a family of 6-DOF Stewart platform motion bases and driver/gunner CAT crewstations [1,2,12]. The Ride Motion Simulator (RMS) and Turret Motion Base System (TMBS) are hydraulically-actuated Stewart platforms designed to provide realistic motion cues to the operators driving in a virtual environment. The position, velocity, and acceleration inputs to the motion bases came from a high-fidelity tracked vehicle model implemented in SimCreator [7]. The vehicle model interacted in real time with CHPSPerf, which is a Matlab/Simulink based hybrid electric power system model [10]. Two crewstations provided realistic driver and gunner visuals via touch-screen interfaces and a yoke/pedal combination. Whether driver or gunner, the appropriate touch-screen interface was displayed along with a high-resolution 3D rendering of the surroundings and appropriate audio cues. The surroundings include the terrain, roads, trees, buildings, power lines, and other friendly or enemy vehicles. The TSL used OneSAF Test Bed (OTB) to provide the operational context in which the soldiers perform their missions [13].

The P&E SIL houses a full scale combat hybrid electric power system in a highly instrumented laboratory environment [3]. 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 [4]. 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 [4]. Non-mobility loads were imposed on the power system using a 250kW Aerovironment AV-900 bi-directional power supply [6]. For DCE 2.x, the power system under test was similar to the 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.

Neither the TSL nor the P&E SIL are portable, so to achieve the real-time bi-directional interaction between the driver/gunner and power system hardware, an Internet-enabled configuration was chosen to couple the two labs with the soldier-in-the-loop and hardware-in-the-loop (Figure 2).

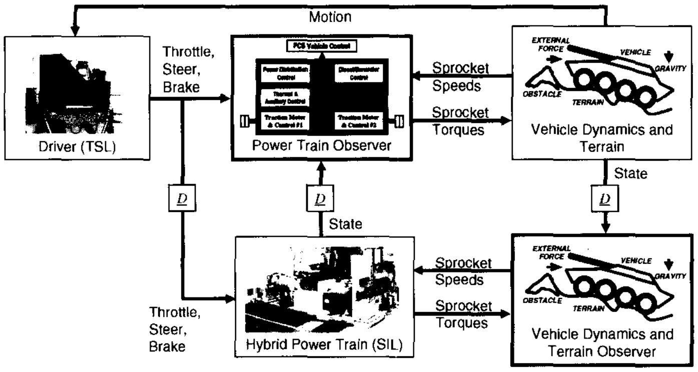


Figure 2: System Layout (top boxes in TSL, Michigan; bottom two in P&E SIL, California)

Identical 3D high-fidelity tracked vehicle mobility models were implemented at both locations. The TSL's mobility model interacted in real-time with the Ride Motion Simulator and also the Power Train Observer, CHPSPerf. Driver and gunner commands were sent to the simulated power system, CHPSPerf, which developed simulated traction motor torques. The motor torques independently spun the left and right sprockets which drove the TSL's mobility model over digitized terrain. Simultaneously, the driver and gunner inputs were sent over the Internet to the P&E SIL's power system hardware which, in turn, developed torques and drove the SIL's local mobility model. Because both locations contained separate mobility models, the methods for achieving closed-loop stability at either location remained localized and independent of the Internet communication's delay and jitter. However, using two mobility models opened the possibility that the two would diverge because of differences between simulated and real power system responses.

To manage the divergence, Mobility State Convergence was implemented to facilitate coordinated laboratory operation while keeping both mobility models at the same location in their respective virtual environments. Similarly, Power System State Convergence was used to ensure the TSL's power system model followed the P&E SIL's relevant power system states. Both state convergence implementations used 30Hz updates over a standard Internet connection. A simulation study was performed to evaluate the feasibility of RemoteLink operation, characterize the Internet communication, and develop control strategies [11].

Due to scheduling and technical constraints the DCE 2.0 experiments achieved uni-directional communication from the TSL to the SIL with a series of trained Army tracked vehicle drivers and gunners. This effectively made the SIL a TSL follower and made the TSL's power system response solely a function of the CHPSPerf power system model. The DCE2.1 experiments used engineers as driver and gunner subjects with bi-directional Internet communications and achieved both mobility and power system state convergence at both locations.

Safety Considerations

The experiment included human presence at both the TSL and P&E SIL facilities where the 6-dof motion base platform and the power system HWIL were located, respectively. As such, safety was of the utmost concern, first with regard to human safety and secondarily with regard to equipment protection. As stand alone devices, both the 6-DOF motion base simulator and the P&E SIL possess robust, multi-layer safety interlock and fault detection systems which are intended to detect and prevent hazardous situations from developing. However, by coupling the systems together, the possibility of new hazards are introduced which are unknown to the stand-alone systems. These additional hazards arise from three potential sources (1) the unreliability of the chosen communication channel, the Internet, (2) the stability of the closed loop system, and (3) the divergence of the state convergence algorithm.

Internet communications delay and drop rate characteristics between the TSL and SIL were benchmarked. Results indicated that the packet loss rate was approximately 0.1% and the most likely round trip time was 94ms with some jitter in the network delay. Since the loss rate was so low, we chose to accept that some packets would be lost and chose UDP/IP as our communication protocol over TCP/IP. The benefit of TCP's retry feature was not worth the risk of a 1 (s) or more delay during the retry attempt. At approximately 30Hz, losing one UDP packet only cost 0.03(s) with another packet right behind. As such, our design did not assume a particular update rate, instead each control action was tied to a particular event, that being the arrival of a new packet. This approach has been shown robust in the presence of the unreliable and multi-path nature of the Internet [14]. Additionally, to guard against Internet connection loss the packet delay and update interval were continuously monitored and reported to the safety subsystem.

To address the stability of the system, the control actions in the state convergence were intentionally designed to drive the states to their reference values over a period of time which is greater than the network delay. In this way, the control action is not likely to over correct before the arrival of updated information. Delay in a closed loop system is a notorious source of instability. Normally this is caused by error computation using data which are time-skewed by the delay. By, using an event-based approach similar to that described in [14], error can be computed using time-synchronized data thus alleviating delay-based instabilities. The system was too complex to rigorously prove stability. Therefore we tested extensively prior to running the experiment with people or hardware in the loop to obtain confidence that the system would be stable.

Finally, state convergence algorithm divergence was monitored continuously and compared to preset thresholds to assure the errors remained bounded. In the event the threshold was violated, the SIL would drop out of the experiment and the TSL would continue in stand-alone mode. Also, automated safeguards were implemented where the TSL and SIL both sent status and health signals to the other location. In the event that a health signal became false, the RemoteLink connection would be broken, the SIL shut down, and the TSL experiment would continue in stand alone mode. The TSL monitored three aggregate P&E SIL status messages: (1) vehicle dynamics status, (2) power system hardware status, and (3) mobility state convergence status. Likewise, the P&E SIL also monitored three TSL aggregate status signals: (1) vehicle dynamics status, (2) power system state convergence status, and (3) motion base hardware status.

Control System Design Considerations

The *RemoteLink* technical objectives for the 2.x series of Duty Cycle Experiments are listed below:

- The RemoteLink should maintain realistic driver perception and feel – this means the motion base should ensure realistic driver/gunner inputs (no video game inputs) plus the TSL's driver should perceive a torque response similar to the P&E SIL's power system hardware
- The RemoteLink should facilitate meaningful power system results – this means the P&E SIL's power system hardware should provide realistic performance for a combat hybrid electric vehicle including realistic tracked vehicle mobility loads.
- The RemoteLink should ensure state tracking at both sites – this means both mobility model positions and velocities should remain coordinated and the TSL's power system model should follow the real hardware's bus voltage, both in the presence of variable Internet communication delays.

For mobility state convergence, the global XY position and vehicle heading (yaw) were determined sufficient to coordinate both vehicle models.

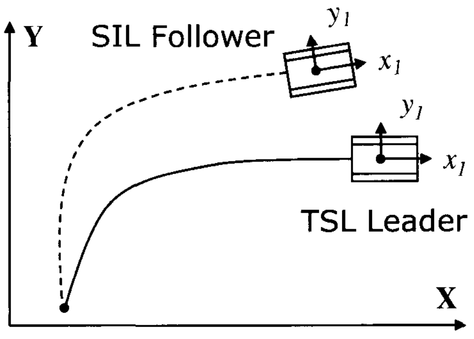


Figure 3: Mobility State Convergence Ensures Both Models Remain Close

Vehicle velocity convergence is achieved if position time histories match, but the opposite is not true. Also, the track-terrain interaction induces sprocket and motor speed convergence when both vehicle positions track well. During preliminary simulation-based testing it was found that the sprocket speed error changed with frequency higher than the network update rate. However, the global position and yaw error signals changed at low enough frequency such that the 30 Hz Internet update rate provided good signal resolution. Network update rate was the most important factor for mobility state convergence. Because the TSL driver throttle, steer, and vehicle position all arrived at the SIL in the same time stamped UDP packet the stability of mobility state convergence was independent of the one-way delay. Mobility state convergence error was computed in the SIL's delayed time frame,

$$e_{mobility\ SC}(t+\Delta_1) = y_{des}(t) - y_{act}(t+\Delta_1)\,.$$

The error was also *used* in the delayed time frame. This means the driver inputs, vehicle states, and SIL state adjustments were consistent with each other, independent of the delay, and simply caused the SIL's vehicle model to lag behind the TSL by the one-way delay, Δ_1.

The objective set of states for Power System State Convergence included bus voltage, battery state of charge, engine speed and multiple coolant temperatures. To meet schedule constraints scope was reduced to include bus voltage for DCE 2.x. The TSL's simulated bus voltage was sent to the SIL with the same UDP packet containing the driver inputs and vehicle position. The bus voltage error was then computed in the SIL in the time frame delayed by Δ_1, which was $t_{SIL} = t_{TSL} + \Delta_1$. Using absolute times, the error was

$$e_{power\ system\ SC}(t+\Delta_1) = V_{bus,SIL}(t+\Delta_1) - V_{bus,TSL}(t)$$

Neglecting SIL computation time, the bus voltage error computation was performed in the SIL and, although delayed, represents an error consistent with the time history of the SIL and TSL. However, to be used in the TSL, the error experienced the second network delay, Δ_2. Using absolute times, the power system state convergence adjustment used in the TSL was at $t + \Delta_1 + \Delta_2$ and a function of error computed with two different, although consistent, bus voltages,

$$e_{power\ system\ SC}(t+\Delta_1+\Delta_2) = V_{bus,SIL}(t+\Delta_1) - V_{bus,TSL}(t)$$

This is the reason power system state convergence stability was influenced more by the round trip delay than mobility state convergence. Power system state convergence implemented changes in the TSL's present time with errors computed Δ_2 seconds in the past. Also, that error was computed using a TSL bus voltage sampled at $\Delta_1 + \Delta_2$ seconds in the past. Despite delay influencing the error, stability was maintained with both mobility and power system state convergence.

Mobility State Convergence

Mobility state convergence is intended to ensure both vehicle mobility models remain within some maximum distance of each other within the virtual environments. Position and heading agreement were particularly important while traversing bridges and negotiating other obstacles that would have generated significantly different terrain response in the TSL versus the SIL. Since the TSL was man-rated and operated with a soldier-in-the-loop, all mobility model state adjustments were made in the SIL. The TSL vehicle was the mobility leader and the SIL model the follower. Focusing on the SIL vehicle, the mobility state convergence problem is a nonlinear MIMO system with variable time delay, three inputs, and three outputs. The time delay is not modeled explicitly, therefore the nonlinear system in the SIL may be represented with,

$$\dot{\hat{x}} = f(\hat{x}) + g \cdot u + g_{SC} \cdot p \tag{1}$$

The $(g_{SC} \cdot p)$ term represents the mobility state convergence inputs. The $f(x)$ represents the nominal plant with control inputs, $(g \cdot u)$. The plant and $(g \cdot u)$ control inputs are discussed below after mobility state convergence inputs and outputs are defined.

The final set of outputs were X position, Y position, and heading in the inertial, or terrain frame, ψ. These outputs had no observability problems since both vehicle trajectories remained unique and were generated in simulation. Other possible outputs considered were left and right sprocket speed, vertical position in the terrain database, vehicle pitch and roll, and *xyz* vehicle velocity. Due to network update rate reasons discussed above, the sprocket speeds were removed from the output vector. Also, the vertical terrain database position and pitch and roll angles were removed from the set of control outputs because, assuming vehicle positions, headings, and terrain databases were coordinated, the local vehicle model dynamics and terrain interaction would produce similar vehicle states without explicit control action.

$$\hat{y} = [X \quad Y \quad \psi]^T \tag{2}$$

In addition, several design choices were made to reduce the set of mobility SC inputs from several down to three. In the simulation study documented previously [11], both H-infinity and Sliding mode control methodologies were evaluated along with two input vector topologies. The first input topology associated with Sliding mode used three fictitious skyhook inputs to achieve mobility state convergence. Two linear accelerations were inserted into the body-fixed 6-DOF equations of motion, $p_{longitudinal}$ and $p_{lateral}$ along with one angular acceleration, p_{yaw}.

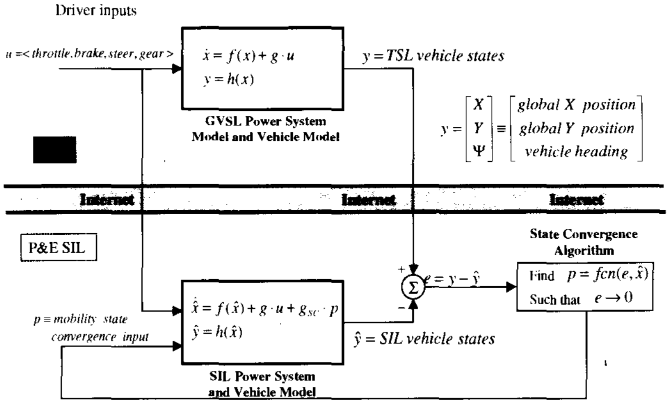


Figure 4: Mobility State Convergence Control System Diagram

These fictitious accelerations provided controllability guarantees in the presence of power system and track-terrain saturation. No limitations in the track-terrain model or power system model would prevent the skyhook inputs from achieving state convergence. Also, skyhook inputs retained clear physical meaning by entering the equations of motion as acceleration inputs and provided gradual position and velocity adjustment. Velocity level inputs would have caused instantaneous momentum changes and as a result would have risked multiple shutdown conditions while interacting with the power system hardware. Abrupt vehicle speed changes translate into abrupt motor speed setpoint changes which could cause over-current shutdown conditions.

The second input topology previously evaluated used throttle and steering inputs to achieve mobility state convergence. This topology was associated with the H-infinity methodology which remained a viable option, however was not pursued for these experiments. The advantage of using throttle and steering inputs were simplicity and straightforward interpretation and implementation. The risk with these inputs is loss of controllability. Either power system saturation or high-slip track-terrain conditions could cause the control inputs to no longer affect the outputs, at least for some time. Neither of these conditions presented themselves for extended periods during normal Duty Cycle Experiment operation.

The final choice of mobility SC control inputs was a combination of the two input topologies previously studied. The output vector was composed of lateral skyhook acceleration, $p_{lateral}$, yaw skyhook angular acceleration, p_{yaw}, and the driver's augmented throttle input, th_{SC},

$$p = [p_{lateral} \quad p_{yaw} \quad th_{SC}]^T \tag{3}$$

The inputs from (3) and outputs from (2) define the plant and nominal inputs in (1). In the SIL they contain both simulated and real hardware states. The plant's presentation as $f(\hat{x})+g\cdot u$ with additional mobility state convergence inputs is an abstraction that encompasses multiple subsystems and closed loop control systems within. For example, because the throttle augmentation is an input in (3), the $f(\hat{x})+g\cdot u$ in (1) represents not only the 6-DOF vehicle model's equations of motion, but also the engine/generator components and controllers, the traction motors with their current and speed controllers, the battery and its control, the bus voltage and control, the dynos and mobility load emulation control, and the driver's throttle/steer/gear inputs.

Power System State Convergence

The goal of power system state convergence was to cause the relevant states of the TSL power system model, CHPSPerf, to track the relevant states in the real SIL power system. The power system state convergence problem was also a nonlinear system with variable time delay and reduced to a SISO system. A PI controller was selected to achieve reasonable bus voltage tracking for DCE 2.1. The controller used bus voltage error to apply an artificial current to the high voltage bus model in the TSL. This artificial current drives the TSL's bus voltage to SIL's hardware voltage. The gains in the PI controller were tuned in order to meet two goals: 1) TSL bus voltage tracking the P&E SIL bus voltage 2) The driver in the TSL shouldn't notice any sudden vehicle oscillations due to the artificial current supplied by the powertrain observer.

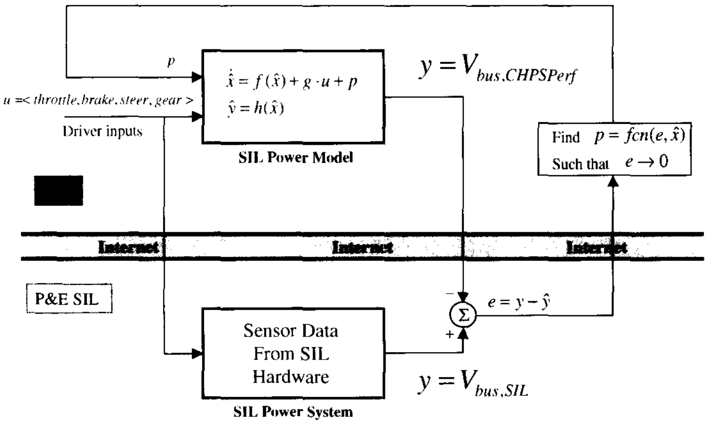


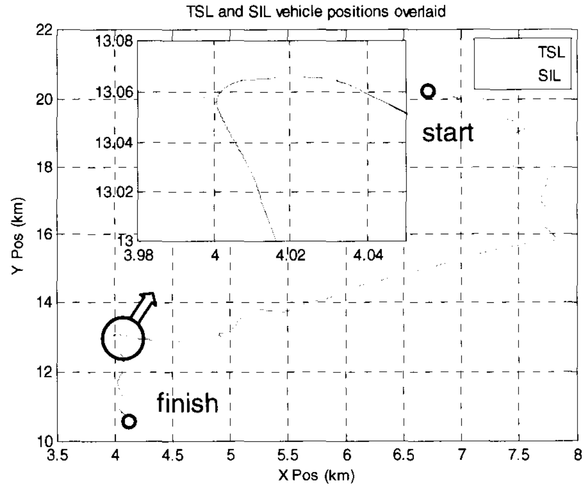
Figure 5: Power System State Convergence Control System Diagram

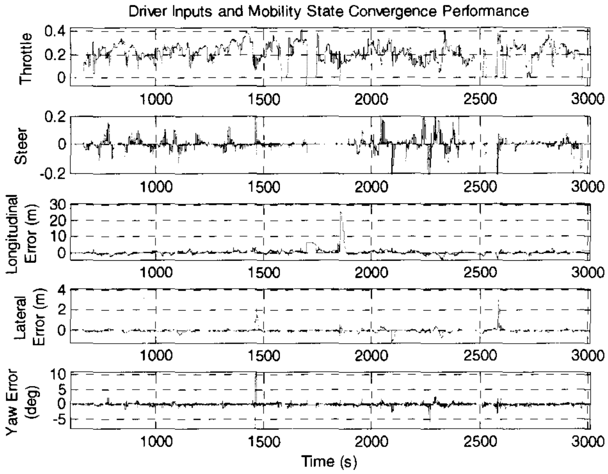
Duty Cycle Experiment Results

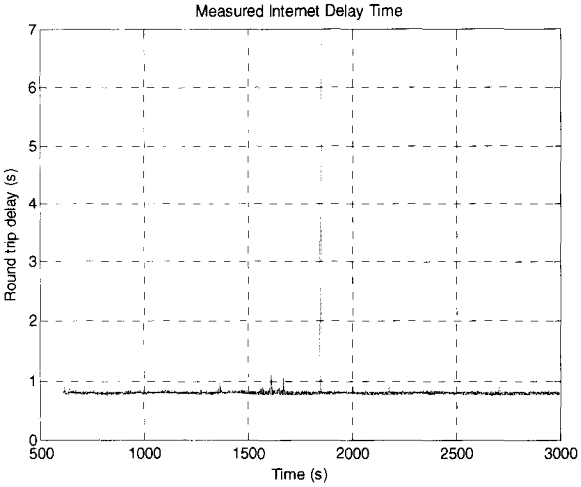
This section presents DCE2 experiment results focusing on state convergence performance and influence on both laboratories. The results show both mobility state convergence and power system state convergence facilitating a 42 minute duty cycle experiment with real time bi-directional signal flow between both laboratories.

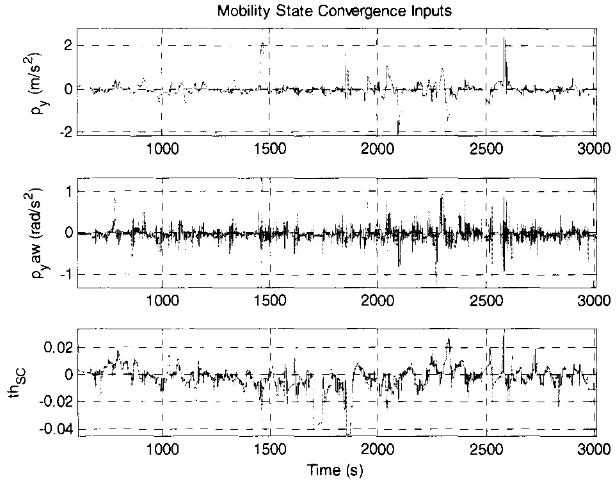
Mobility Results

The XY plot below is a top-view with both TSL and SIL positions overlaid. Mobility state convergence achieved an average of approximately 5(m) error or less with one excursion of 30(m). The excursion event resulted from an unexplained ~7(s) TSL computer freeze. This is indicated by the spike in the network delay figure below. There is no discernable difference in vehicle positions on the plot below because of scale. The course was approximately 8 miles long and took approximately 40 minutes to drive.





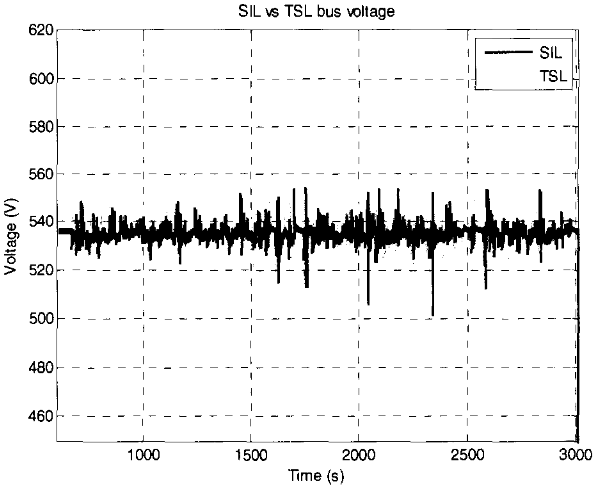




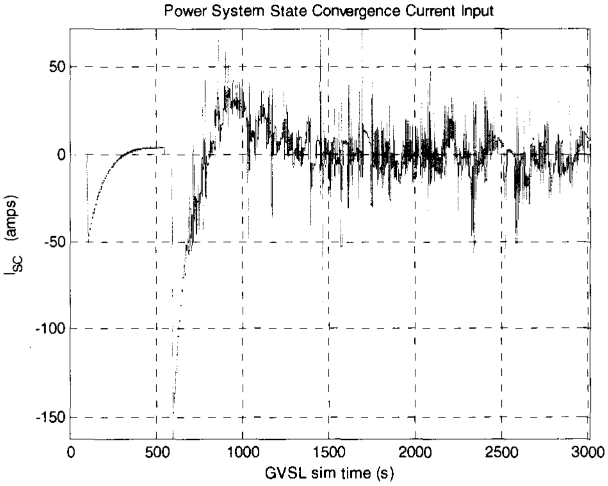
The figures above indicate the TSL and P&E SIL vehicles stayed within a few meters of each other through the entire *RemoteLink* experiment. Exceptions were few and resulted from computer operating system unresponsiveness which caused large communication delays.

Power System Results

The plots below show the bus voltage and artificial current inputs for a representative DCE 2.1 experiment.



The bus voltage errors stay in a reasonable range for the duration of the run. Similarly, the artificial power system state convergence current input stays within 100 amps with one exception.



The product of the bus voltage and artificial current, I_{sc}, is the artificial power that is supplied to the CHPSPerf power system by the powertrain observer. The integration of the artificial power over the time duration of the Fort Knox run results in a quantity called "leaked energy", which is discussed below.

Leaked Energy

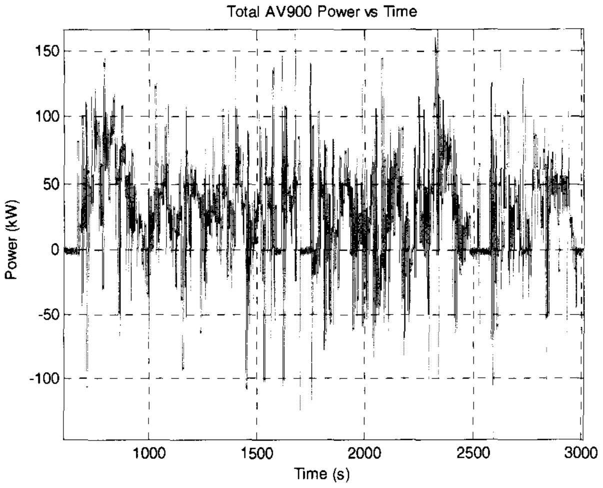
Leaked energy is calculated for both the powertrain observer running in the TSL and for the vehicle dynamics observer running in the P&E SIL. As described above, power system leaked energy results from the integration of artificial power over the length of the experiment. This integration results in units of Joules for leaked energy. In the vehicle dynamics observer, the leaked energy is calculated from the product of skyhook accelerations, masses, and velocities integrated over the length of the run. These quantities are normalized in the powertrain observer and in the vehicle dynamics observer in order to obtain percent leaked energy. In the vehicle dynamics observer, leaked energy is normalized by the total energy input to the vehicle dynamics model, which includes the mechanical energy coming from the left and right motors and the energy provided by the artificial skyhook acceleration inputs to the vehicle model. In the powertrain observer, the leaked energy is also normalized by the total energy input to the high voltage bus, which includes the input energy from the battery and the input energy from the generator. For DCE2 Run 1, the vehicle dynamics leaked energy was 0.6 percent and the power system leaked energy was 2 percent.

Leaked energy percent is a metric that characterizes how effectively the model approximates the equivalent hardware while operating under realistic real-time conditions. In the case of the TSL power system model, a small leaked energy value of 0.6% indicates that the model closely matches the behavior of the real hardware. Likewise, a 2% leaked energy value for the mobility model in the P&E SIL indicates that the driver and gunner inputs were realistically implemented.

Non-Mobility Loads

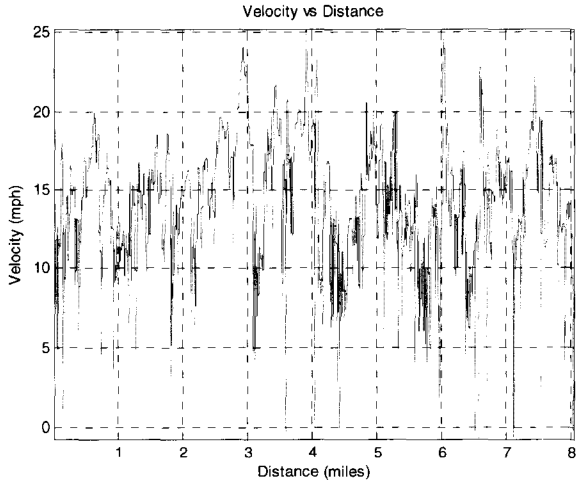
As mentioned above, the DCE's SIL power system differed from the objective power system by simulating one traction motor rather than implementing both traction motors in hardware. The simulated traction motor and sensor provided inputs to the SIL mobility model's virtual driving environment but did not implement the real loads on the hardware power system. To emulate the simulated motor's power draw in hardware, the computed power was added to the AV-900's non-mobility load power for hardware interaction with the real power system.

The AV900 is a bi-directional power supply that can push or pull up to 125 kW of power to or from the bus. These loads include hotel loads, PFN power draws, auto-loader power draw corresponding to the main gun fire, and active protection system power draws. The plot below shows the total AV900 power draw and from the high voltage bus during a representative DCE 2.1 experiment.

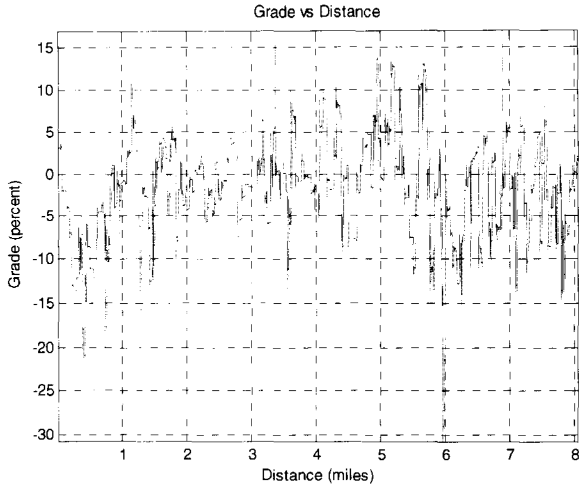


A Representative Duty Cycle

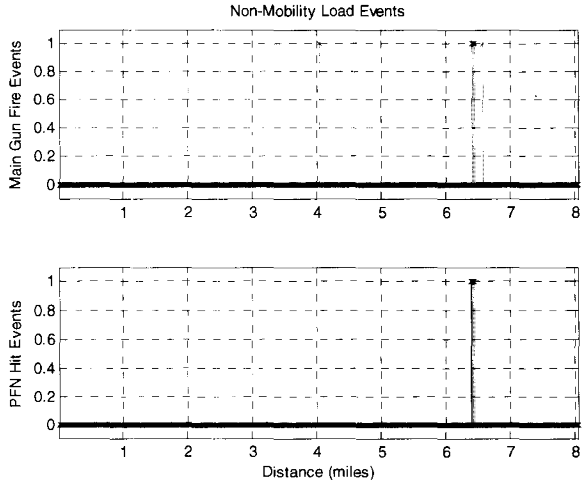
Experimental results from a 42 minute, 8 mile drive with the TSL and P&E SIL communicating over the Internet with bi-directional *RemoteLink* signals are presented below. These figures are plotted with distance as the independent axis. This allows direct comparison to other vehicles with different architectures or components.



The vehicle's speed versus distance varies from stopped to a top speed of 25mph. Cross-referencing the speeds with the main gun events and pulsed power events indicates the vehicle was both stopped and driving while engaging the OPFOR SAF entities.



Cross referencing the speed figure with the grade versus distance figure, it appears the driver stopped on a 30% grade, most likely to scan a horizon or the other side of the hill, then moved forward and engaged the SAF enemy vehicles.



Pulse Forming Network (PFN) events happened in rapid succession at the 6.3 mile distance which is right after the driver stopped to scout out the area on a 30% hill. The PFN hits were imposed on the SIL's power system with a 50kW power draw for 4 seconds using the AV-900. The total PFN energy cost was 200kJ. Main gun firing events occurred at roughly 4 and 6.5 miles into the course while engaging enemy SAF forces. Power system draws associated with these events were 1kW for 4 seconds and implemented in the SIL using the AV-900.

Conclusions

The *RemoteLink* architecture facilitated duty cycle experiments in Summer 2006 using bi-directional real-time communications over the open Internet using Army assets at laboratories 2,450 miles apart. The duty cycle experiments featured live soldier-in-the-loop inputs with 6-DOF motion and sound feedback, CAT crewstation driver and gunner interfaces, 3D scenario images with other SAF entities, and vehicle models interacting with a full-scale combat hybrid electric power system in real time. The resulting electrical and mechanical duty cycles can be used to further iterate designs for the Army's future vehicle systems and components. Future Duty Cycle Experiment plans include improved power system hardware, improved pulsed-power loads, improved mobility load emulation, improved round-trip network delay, and improved SAF and scenario interaction.

A control scheme was developed to couple two dynamical systems over the Internet and was shown to perform adequately in the presence of stochastic delay and packet loss. The control scheme adopted an event-based approach triggered by the arrival of new information. In this way, it was not necessary to estimate or compensate for the jitter in the network delay or the effects of packet loss.

References

1. Brudnak, M.; Nunez, P.; Paul, V.; Mortsfield, T.; Shvartsman, A.; Perera, H.S.; Smith, W.; Mohammad, S.; Pozolo, M., "Human-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 1", Paper SIW-06S-080, Simulation Interoperability Standards Organization (SISO), Orlando, FL, April 2006.
2. Paul, V.; Brudnak, M.; Ueda, J.; Shvartsman, A., "Simulation-based Hybrid Electric Combat Vehicle Duty Cycle Measurement", Intelligent Vehicle Systems Symposium, NDIA, Traverse City, MI, June 2006.
3. Miguel Simon, Marc Compere, Thomas Connolly, Charles Lors, Wilford Smith, Mark Brudnak, "Hybrid Electric Power and Energy Laboratory Hardware-in-the-Loop and Vehicle Model Implementation," *SAE 2006 World Congress & Exhibition*, Military Vehicle Modeling and Simulation session, April 2006, Detroit, MI, USA
4. John Kajs, Marc Compere, Eugene Danielson, "Power System Upgrade for TARDEC System Integration Lab," presented at *The Sixth International All Electric Combat Vehicle Conference 2005 (AECV 2005)*, Bath, England, June 13-16, 2005
5. Marc Compere, Miguel Simon, John Kajs, Mike Pozolo, "Tracked Vehicle Mobility Load Emulation for a Combat Hybrid Electric Power System", presented at *The Sixth International All Electric Combat Vehicle Conference 2005 (AECV 2005)*, Bath, England, June 13-16, 2005
6. AV-900 Installation, Operation, and Maintenance Manual, *AeroVironment Inc*, Monrovia, California
7. Realtime technologies, Royal Oak, MI, www.Simcreator.com
8. McCullough, M. K. and Haug E. J., "Dynamics of High Mobility Track Vehicles," ASME Design

Engineering Technical Conference, Cincinnati, Ohio, Paper No. 85-DET-95, 1985.
9. Wong, J.Y., *Theory of Ground Vehicles, 3rd Ed.*,John Wiley & Sons, ISBN 0-471-35461-9, 2001.
10. Wilford Smith and Patrick Nunez, "Power and Energy Computational Models for the Design and Simulation of Hybrid-Electric Combat Vehicles", SPIE Paper No. 5805-02, Paper Presented at Simulation Science IX, Orlando, FL, 28 March – 1 April 2005.
11. Jarrett Goodell, Marc Compere, Miguel Simon, Wilford Smith, Ronnie Wright, Mark Brudnak, "Robust Control Techniques for State Tracking in the Presence of Variable Time Delays," *SAE 2006 World Congress & Exhibition*, Military Vehicle Modeling and Simulation session, April 2006, Detroit, MI, USA
12. Truong, N.; Paul, V.; Shvartsman, A,, "Integration of the CAT Crewstation with the Ride Motion Simulator (RMS)" *SAE 2006 World Congress & Exhibition*, Paper 2006-01-1171, April 2006, Detroit, MI, USA
13. OneSAF Website, http://www.onesaf.org.
14. I. Elhajj, N. Xi, W.K. Fung, Y.H. Liu, Y. Hasegawa, T. Fukuda, "Supermedia Enhanced Internet Based Telerobotics", in Proceedings of the IEEE, special issue on Networked Intelligent Robots Through the Internet, Vol. 91, No. 3, pp. 396-421, March 2003.

CONTACTS

SAIC authors may be contacted at:

Dr. Marc Compere: CompereM@saic.com
Mr. Jarrett Goodell: GoodellJa@saic.com
Mr. Miguel Simon: SimonM@saic.com
Mr. Wilford Smith: SmithW@saic.com

Science Applications International Corporation
8303 N. MoPac Expy. Suite B-450
Austin TX 78759
(512) 366-7812

The U.S. Army TARDEC author may be contacted at:

Dr. Mark Brudnak: brudnakm@tacom.army.mil

U.S. Army Tank Automotive Research Development and Engineering Center
6501 E. 11 Mile Rd.
AMSRD-TAR-N/157
Warren, MI 48397-5000
(586) 574-7355

DEFINITIONS, ACRONYMS, ABBREVIATIONS

DCE: Duty Cycle Experiment

OneSAF: A composable computer generated force that can represent a full range of operations, systems, and control processes from entity to brigade level with variable fidelity supporting multiple Army modeling and simulation domain applications.

OPFOR: Opposing or opposition forces within a SAF environment

OTB: OneSAF Test Bed

P&E SIL: Power and Energy SIL

SAF: Semi Automated Forces

SIL: System Integration Laboratory

TSL: TARDEC Simulation Laboratory