INVESTIGATION OF CONTROL ALGORITHMS FOR TRACKED VEHICLE MOBILITY LOAD EMULATION FOR A COMBAT HYBRID ELECTRIC POWER SYSTEM

Jarrett Goodell
SAIC
Austin, TX

Wilford Smith
SAIC
Marietta, GA

Byron Wong
U.S. Army TARDEC
Warren, MI

ABSTRACT

The United States Army Tank Automotive Research, Development and Engineering Center (TARDEC) is actively investigating and researching ways to advance the state of combat hybrid-electric power system technology for use in military vehicles including the Future Combat Systems' family of manned and unmanned ground vehicles. Science Applications International Corporation (SAIC) is the lead contractor for operating the Power and Energy System Integration Laboratory (P&E SIL) in Santa Clara, CA. The P&E SIL houses a combat hybrid electric power system including a diesel engine, generator, high voltage bus, DC-DC converter, lithium ion battery pack, left and right induction motors, and left and right dynamometers. The power system is sized for a 20-22 ton tracked vehicle. The dynamometers are responsible for emulating loads that the vehicle would see while running over a course.

This paper discusses the control system design for achieving mobility load emulation. Mobility load emulation is defined as the ability of the measured left and right sprocket speeds to track the left and right sprocket speeds in the vehicle model. Simulated and experimental results are presented for various load emulation strategies. Several algorithms are investigated, and a final algorithm is chosen based on a standard control systems analysis. The algorithms developed are designed in a modular fashion such that they can function with combinations of vehicle models and dynamometers other than the vehicle model and dynamometers used at the P&E SIL.

INTRODUCTION

The US Army TARDEC and Science Applications International Corporation are examining methods to improve the state of combat hybrid-electric power system technology for the benefit of the future force, including the Future Combat Systems Manned Ground Vehicle (FCS MGV) and Un-manned Ground Vehicle (FCS UGV) programs. Science Application International Corporation (SAIC) is the lead contractor for designing, developing, and maintaining the Power and Energy System Integration Laboratory (P&E SIL) for US Army TARDEC. The P&E SIL contains a combat hybrid electric power system sized for a 20-22 ton tracked vehicle. The power system is a series hybrid power train, and it is packaged into an FCS MGV-like hull such that thermal interactions and electro-magnetic noise become significant. The series hybrid power system housed by the P&E SIL is most commonly referred to as the HERMIT, or Hybrid Electric Reconfigurable Movable

Integration Testbed (see Figure 1 below). The physical outputs of the HERMIT power system are the left and right sprockets, which connect directly to the left and right bi-directional dynamometers (blue items on far left and right). The dynamometers are the mechanisms used to achieve mobility load emulation. The dynamometers work hand-in-hand with the left and right torque sensors and the Tracked Vehicle Virtual Proving Ground (TVVPG) vehicle model. More details on the preceding interactions are discussed in the control system section of the paper. In addition to discussion of the HERMIT power system and TVVPG vehicle model, this paper investigates several control strategies used to achieve mobility load emulation.

Figure 1: HERMIT Power System

HERMIT SERIES HYBRID POWER SYSTEM

The HERMIT series hybrid power system includes a 250 kW diesel engine, 410 kW generator, 600 V DC bus, 150 kW continuous DC-DC Converter, an 18 kW-hr lithium ion battery pack, and left/right 410 kW induction motors. A schematic of the power system is shown in Figure 2. The HERMIT power system components are sized for a 20 to 22 ton skid-steered, tracked vehicle. The left and right traction motor output shafts are connected directly to the left and right dynos by means of a 16.6 gearing and a mechanical coupling.

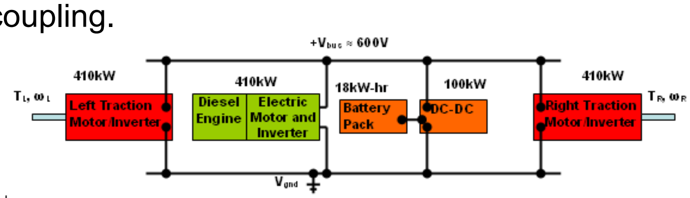

Figure 2: HERMIT Power System Layout

HERMIT DYNAMOMETERS

The purpose of the HERMIT dynamometers is to apply loads to the HERMIT power system that correspond to the interaction between the vehicle dynamics model and the simulated terrain. The dynamometer specifications were determined by the maximum torque, speed, and power characteristics for a 20 to 22 ton skid-steered tracked vehicle. Existing data was found (see Figure 3 below) for a 26 ton Jaguar tracked vehicle and was used as a reference point.

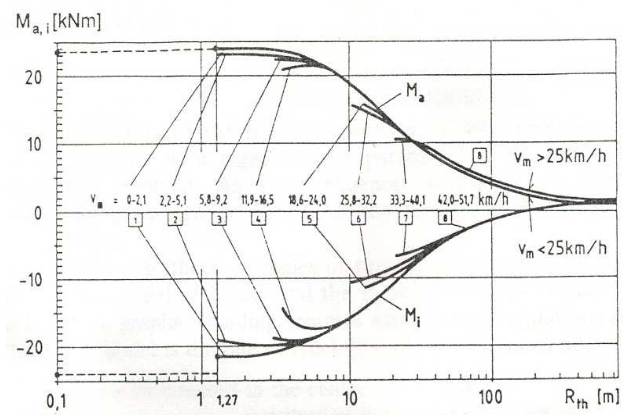

Figure 3: Experimental Data for a 26-ton Jaguar Tracked Vehicle from [1]

The dynamometer performance specifications of the P&E SIL dynamometers relevant to a control systems analysis are listed in Table 1.

Table 1: P&E SIL Dyno Specs

Single-pole time constant for T_{actual} / T_{cmd} transfer function	~1ms
Torque controller communication rate (T_{cmd} updates)	1000 Hz
Motor current controller feedback loop update rate	3000 Hz
Dyno PI speed loop update rate	1000 Hz
Speed command communications rate (ω_{cmd} updates)	500 Hz
Continuous power rating (per side)	800 kW
Max power rating (per side)	1000 kW
Gearbox continuous power rating	450 kW

Figure 4 below shows the performance envelope of the P&E SIL dynamometers. Note that both the continuous and the intermittent torque plots are shown. In addition, notice the curvy trajectories that mostly fall inside the envelope of the continuous and intermittent torque/speed plots. The curvy trajectories are the vehicle model's sprocket torques for given virtual vehicle speeds. This plot indicates that the dynamometers are sized appropriately for the TVVPG vehicle model used to run HERMIT through virtual mission profiles.

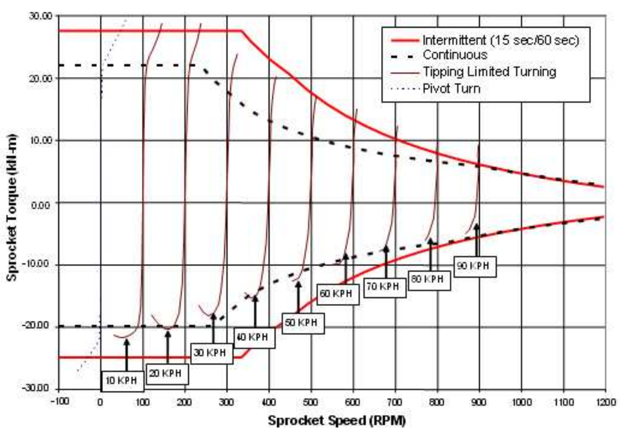

Figure 4: HERMIT Dynamometer Steady-State Capability in High Gear Range and Modeled Tracked Vehicle Mobility Loads

HERMIT VEHICLE MODEL

The purpose of the HERMIT vehicle model is to simulate the dynamics between a 20-22 ton skid-steered tracked vehicle and a virtual terrain. The HERMIT vehicle model was developed by SAIC and TARDEC in 2003. It is a soft-soil, skid-steered, tracked vehicle model called Tracked Vehicle Virtual Proving Ground or TVVPG [2]. Given a power system's sprocket torques as inputs, TVVPG simulates mobility over a 3D terrain surface using a single 6DOF rigid-body model for the vehicle hull and two rotational track and sprocket subsystems. The tracks' interaction with the terrain surface is represented using a combination of Bekker-Wong soft-soil models [3,4], a longitudinal shear-slip displacement model for tracked vehicles [5], and a newly developed lateral shear slip displacement model [6]. The track-terrain interaction model is parameterized in an effort to account for differences in vehicle geometry, weight, and terrain type.

With respect to validation of the model, TVVPG was compared against the experimental data shown in Figure 3 for the Jaguar vehicle. This comparison was performed by substituting Jaguar weight and geometry as inputs for the TVVPG vehicle model. Figure 5 below shows an overlaid plot of sprocket torque versus turning radius for the Jaguar experimental data and the TVVPG modeled data. The modeled curves are generated by driving in a spiral on flat ground using the same terrain and Jaguar vehicle geometry as was used in the Jaguar experimental data.

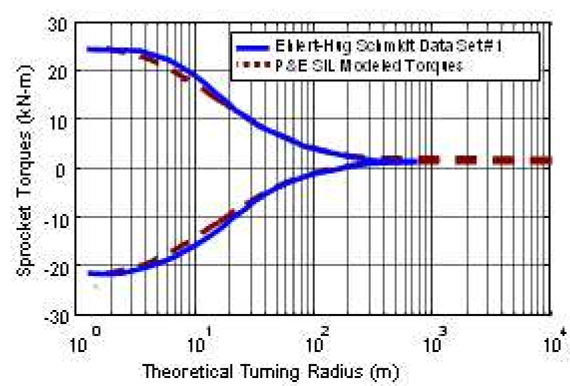

Figure 5: Representative Dataset Comparing P&E SIL's Tracked Vehicle Model to Ehlert-Hug-Schmid Experimental Data

CONTROL SYSTEM LAYOUT

Mobility load emulation using a simulated vehicle model can be viewed as a dynamometer speed control problem with tracking and disturbance rejection objectives.

In this framework, the dynamometer motors represent actuators receiving commands from speed controllers inside the TVVPG vehicle model. The tracking references for the speed controllers come from sprocket speeds computed by the TVVPG model. Thus, to the extent that the dynamometers can achieve their commanded speeds, the complete HERMIT control system achieves tracked vehicle mobility load emulation. Figure 6 illustrates the HERMIT control system layout used to achieve mobility load emulation with speed control of the dynamometers. It also outlines relevant communication rates, sensors, and actuators. Significant items in Figure 6 include the power system, torque and speed sensors, the dynamometer motors, inverters and controllers, the driver's station, and the 3D vehicle model.

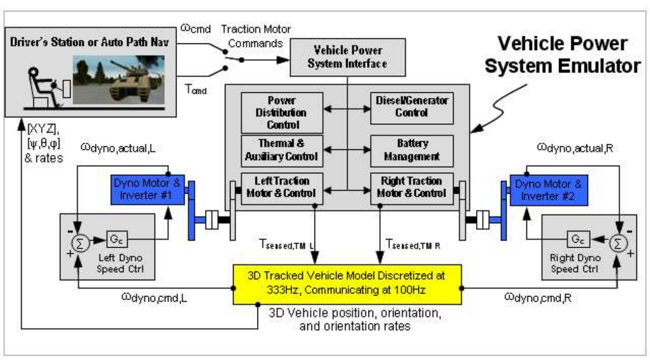

Figure 6: Mobility Load Emulation Layout

Shown on the top left portion of Figure 6, driver inputs are generated either by a live driver-in-the-loop or by an automated waypoint path navigator. The driver input signals include throttle, brake, steer, and power system operating mode. The power system operating mode is a flag indicating the hybrid electric energy management scheme.

As the HERMIT power system traverses a virtual course, the traction motors apply torque to accelerate the vehicle. These torques are transmitted to the left/right sprocket shafts and measured by traction motor torque sensors. Left and right sensed traction motor torques are the inputs to the TVVPG model running in real-time as shown in Figure 7. Depending on the track-terrain interaction and state of the vehicle model, the torque signals will begin to change the modeled left and right sprocket speeds. As the modeled sprocket shafts turn, the vehicle develops traction and drives over the digitized terrain in the virtual environment.

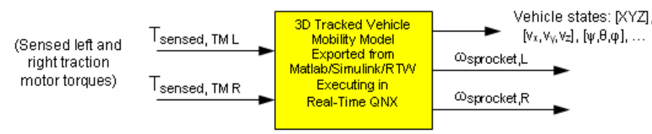

Figure 7: Real-Time Tracked Vehicle Mobility Model Inputs and Outputs

Next, the modeled sprocket speeds are sent to the Load Emulation Controller. Using the dynamometer final-drive gear ratio of 6.58:1, the left and right modeled sprocket speeds are converted to (real) dynamometer speed commands. Figure 8 shows that the traction motor torque is both an input to the vehicle model and also an external disturbance to the dynamometer speed control loop. The torques imposed upon the traction motors by the dynamometers represents terrain and inertia reaction torques. The dynamometers, as discussed above, are sized larger than the traction motors to ensure the dyno motors can achieve their commanded speeds. A detailed control system synthesis is presented in the predecessor to this paper [7]. Methods are shown for disturbance rejection and elimination of steady state dynamometer speed error.

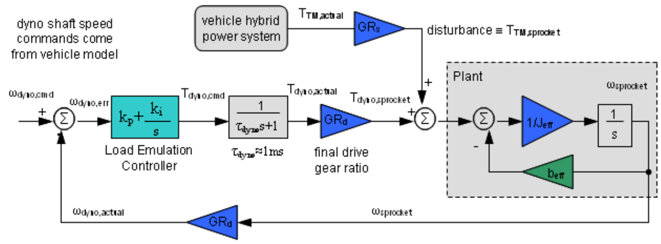

Figure 8: A Dynamometer Speed Control Loop with Traction Motor Torque Disturbance

MOBILITY LOAD EMULATION RESULTS

Three algorithms were investigated for determining the best mobility load emulation algorithm for the HERMIT power system including proportional control, proportional-integral control, and a hybrid proportional/feed-forward control scheme. The meaning of "feed-forward" as used in this context is that the terrain reaction torque, which is computed in the TVVPG model, is used in summation with the proportional control term. Thus, the terrain reaction torque is "fed-forward" to the load emulation controller. All three algorithms were tested in a systematic and sequential manner, beginning with evaluation in the Matlab/Simulink dynamic simulation environment. Detailed Matlab/Simulink models have been developed that incorporate all significant elements of the HERMIT system including the communications and update rates in the controllers, the complete hybrid-electric power system, the complete dynamometer system, the HERMIT power management controller, and the TVVPG vehicle model. Simulations of the HERMIT power system over the Churchville B course on Aberdeen Proving Grounds were used to verify control gains and system stability before proceeding to hardware implementation. By using the Real-Time Workshop extension to the Matlab/Simulink product, the same vehicle and dynamometer controllers developed in the simulation were then used in the real-hardware implementation. This systematic and sequential process for testing mobility load emulation algorithms and running hardware-in-the-loop experiments with the HERMIT system is described in detail in [8]. Simulation results for the three mobility load emulation algorithms are shown in Figures 9-14. Figures 9-11 show the desired and actual left dynamometer speeds overlaid over the 30 minute Churchville run for each mobility load emulation algorithm. Figures 12-14 are the same plots as Figures 9-11, except they are zoomed in on a portion of the simulation where the vehicle is traversing one of the hairpin curves on the Churchville B course.

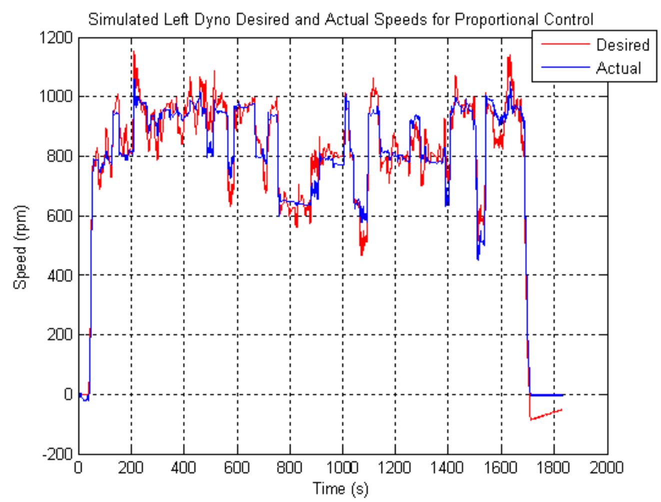

Figure 9: Proportional Control Results

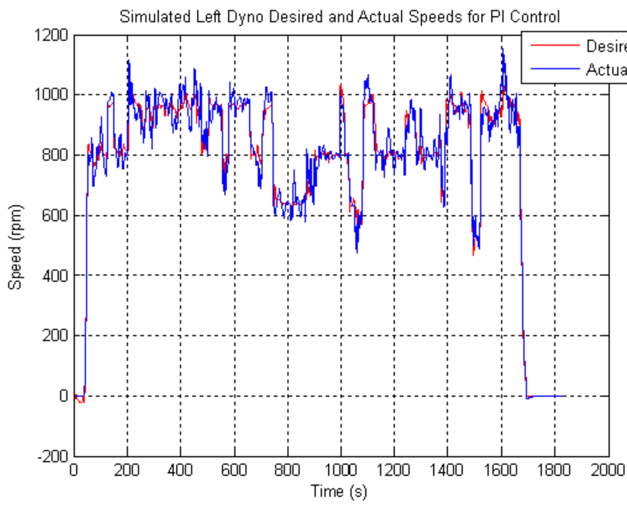

Figure 10: PI Control Results

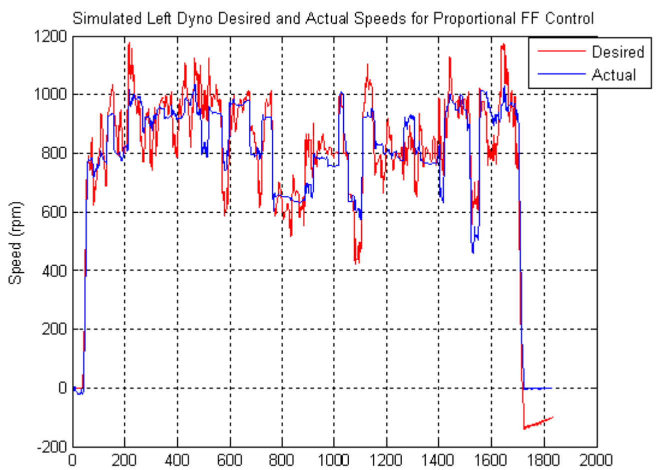

Figure 11: Proportional Feed-forward Control Results

Examination of Figures 9-11 reveals that the PI scheme shows the most promise for elimination of steady-state error between the desired and measured dynamometer speeds. In addition, the figures show that the Proportional/Feed-forward scheme produces the most error between the desired and measured dynamometer speeds. Upon closer examination of the figures, another important finding is revealed. Figures 12-14 illustrate that the P and PI control schemes exhibit un-desired oscillatory behavior. Specifically, the P and PI schemes both exhibit a 75 rpm under-damped oscillation during the hairpin curve, whereas the Proportional/Feed-forward scheme produces a similar oscillation, but the damping behavior is significantly improved over the P and PI schemes. The final noteworthy aspect of the simulation results is the selection of the gains used for each controller. For both the P and PI schemes, lowering the gains below their present values results in the TVVPG model not being able to track the Churchville B course. On the other hand, the Proportional/Feed-forward scheme successfully tracks the Churchville B course with an acceptable and manageable amount of oscillatory behavior and still has margin for the gains to be lowered or raised. Therefore, the Proportional/Feed-forward scheme was selected for implementation with the HERMIT hardware-in-the-loop system.

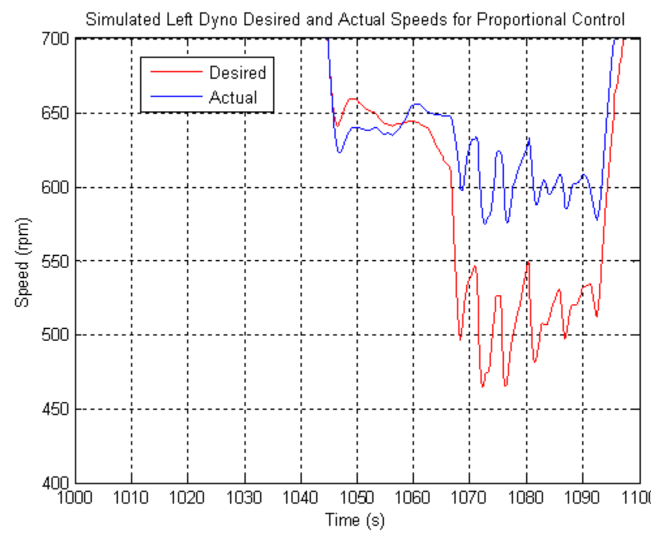

Figure 12: Proportional Control Results Zoomed-in

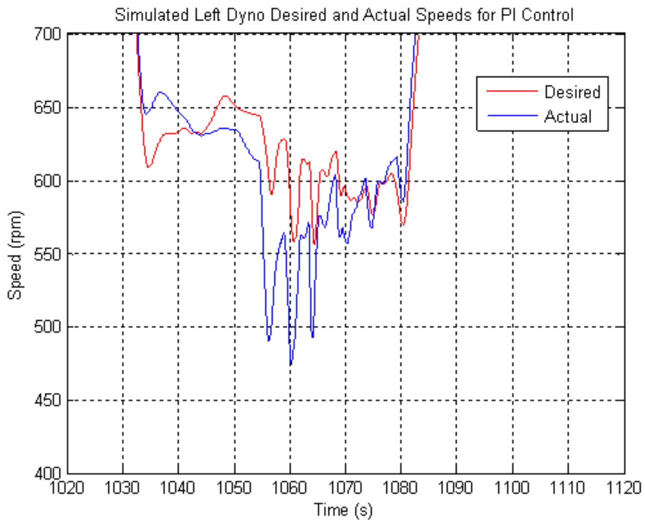

Figure 13: PI Control Results Zoomed-in

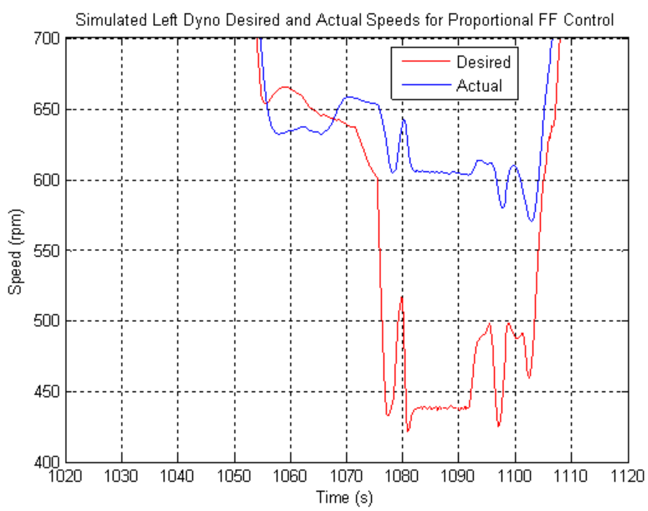

Figure 14: Proportional/Feed-forward Control Results Zoomed-in

The left dynamometer desired versus measured speed plot is shown below in Figure 15 for the hardware-in-the-loop Churchville run using Proportional/Feed-forward control. The scheme has proven to be stable and repeatable over the course of 30 Churchville runs. The maximum error between the desired and actual dyno speeds is 24% for the Churchville run. This condition occurs on one of the large hairpin turns on the Churchville course.

Another comparison of interest is the comparison between simulated and experimental dynamometer measured speeds. Figure 16 shows an overlaid plot of simulated and experimental left dyno speeds. The simulated runs predict the experimental runs to a reasonable degree of accuracy. The presence of speed sensor noise on the experimental plot is the most obvious difference between the simulated and experimental plots. The capability to model the HERMIT system and match the experimental performance to simulated performance is valuable, and it opens the door for other algorithms or methods to be tested in the future to improve system performance.

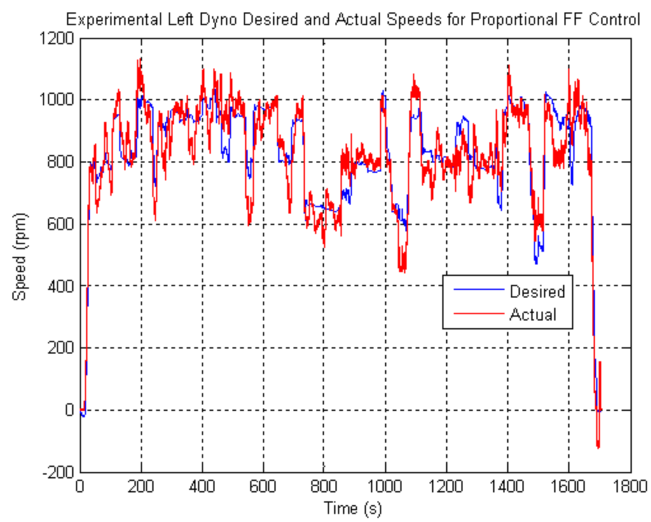

Figure 15: Experimental Results for Proportional/Feed-forward Control

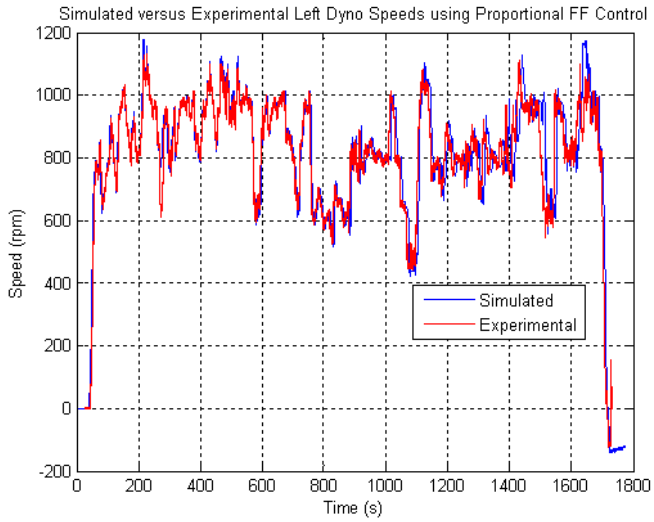

Figure 16: Simulated and Experimental Left Dyno Speeds Over Churchville

CONCLUSIONS AND FUTURE WORK

The US Army TARDEC and SAIC have developed a valuable capability in the area of hybrid electric power system modeling, simulation, and testing. The design of the HERMIT control system and the ability to run repeatable hardware-in-the-loop vehicle model experiments is and will continue to be an asset for testing and development of hybrid electric technology for the future force. This study has developed a successful method for achieving mobility load emulation for a skid-steered tracked vehicle. Due to the modular design of the control algorithms developed, implementation with other hardware will be seamless.

With respect to implementation with other hardware, the HERMIT system is presently being moved from the P&E SIL in Santa Clara, CA to TARDEC in Warren, MI. The system will be tested on a new pair of dynamometers with different specifications than the dynos at the P&E SIL. Therefore, the control system design and stability analysis performed in this study will be re-visited.

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REFERENCES

[1] W. Ehlert, B. Hug, I.C. Schmid, “Field Measurements and Analytical Models as a Basis of Test Stand Simulation of the Turning Resistance of Tracked Vehicles,” Journal of Terramechanics, v.29, no.1, pp.57-69, 1992

[2] M.D. Compere, “Tracked and Wheeled Vehicle Mobility Modeling and Simulation,” presented at *The Fifth International All Electric Combat Vehicle Conference 2003 (AECV 2003)*, Angers, France, June 1-5, 2003.

[3] Wong’s, *Theory of Ground Vehicles, 3rd Ed.*, John Wiley & Sons, 2001.

[4] Bekker, M., Off-the-Road Locomotion, The University of Michigan Press, Ann Arbor, MI, 1969

[5] G. Ferretti, R Girelli, “Modeling and simulation of an agricultural tracked vehicle,” Journal of Terramechanics, v.36, 1999, pp.139-158.

[6] M.D. Compere, “A New Lateral Shear Displacement Model for Modeling Soft-Soil Track-Terrain Interaction”, Manuscript in progress, CompereM@gmail.com

[7] M.D. Compere, Miguel Simon, John Kajs, Mike Pozolo, “Tracked Vehicle Mobility Load Emulation for a Combat Hybrid Power System”, presented at *The Sixth*

International All Electric Combat Vehicle Conference 2005, Bath, UK, June 2005

[8] Miguel Simon, Marc Compere, Thomas Connolly, Charles Lors, Wilford Smith and Mark Brudnak, "Hybrid Electric Power and Energy Laboratory Hardware-in-the-Loop and Vehicle Model Implementation", presented at *2006 SAE World Congress, April 2006*