Real-time Operator-In-The-Loop Simulation for Vehicle Design
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Abstract

The following describes an integrated solution for the conceptual and detailed design and integration of future ground-based vehicles. Due to the fact that these vehicles are designed for the military, they are required to perform complex tasks in very demanding circumstances. Also, the personnel operating these vehicles are required to perform a myriad of complex secondary tasks in conjunction with driving the vehicle. The tight integration of these tasks requires that thorough modeling and simulation be employed during vehicle development.

The solution is an immersive real-time high-fidelity vehicle simulation composed of detailed powertrain models, as well as those for articulated vehicle and terrain dynamics and power loads. The models must also interface with a synthetic working environment, a reconfigurable crew station, as well as data display and capture facilities. The crew station is a full scale physical representation of the man-machine interface enabling engineers to verify requirements and study performance of the operator as well as the vehicle systems and subsystems designs while immersed in a real-time synthetic environment. This simulation is ideal for observing system characteristics such as maneuverability, power management, operator visibility, and crew task loads in realistic operational scenarios. As a result, the real-time operator-in-the-loop simulation provides the ability to optimize vehicle design configurations quickly and inexpensively, prior to fabricating a functional prototype vehicle.

1 Introduction

BAE Systems is a global defense and aerospace company delivering a full range of products and services for air, land and naval forces, as well as advanced electronics, information technology solutions and customer support services. BAE Systems Inc. is the US subsidiary of BAE Systems plc. It provides support and service solutions for current and future defense, intelligence, and civilian systems. Land and Armaments (L&A) is one of the BAE Systems Inc. operating groups which is a global leader in the design, development, production, and service support of armored combat vehicles, major and minor caliber naval guns and missile launchers, canisters, artillery systems, and intelligent munitions. Within BAE Systems' L&A operating group, the Ground Systems (GS) business unit develops and manufactures major ground combat systems for the U.S. Army and Marine Corps, and allied nations, including Bradley, Paladin, M88, and Amphibious Assault Vehicle (AAV).

M88 Hercules **Fig. 1** **M2A3 Bradley**

Ground combat vehicles need to perform complex missions with speed and accuracy. To deliver the mission requirement, trade studies of vehicle performance have to be performed for design to comply with stringent combat conditions and performance requirements. The performance trade studies include vehicle weight changes, various engine powertrain characteristics, suspension design, and ground profiles. In addition, the development of combat vehicles necessitates a solider-centric design to maximize crew member performance and safety.

In the past, many of the design studies have been performed at the component or subsystem level, based on predefined scenarios, including a vehicle acceleration curve, ground profile, and vehicle traversing a course. These predefined use cases allow engineers to perform design analysis through computer simulations and allow them to study the resulting output data. However, these results lack complete platform-level vehicle behavior. The approach lacks interaction of the driver with vehicle performance, and furthermore, also lacks the capability for design engineers to explore a wide range of terrain profiles and various weather conditions that affect vehicle and ground interaction forces.

2 Real-Time Man-In-The-Loop Simulation

To address driver interactions with vehicle design and vehicle performance analysis with various ground profiles, weather conditions, and vehicle configuration changes, BAE GS has developed the capability of real-time man-in-the-loop simulation. The BAE GS man-in-the-loop real-time simulator is the integration of multiple hardware and software components that are interdependently interfaced together. Figure 2 shows the architecture of the simulator. It includes a reconfigurable crew station, synthetic environment with 360 degrees of graphical views, a physics based vehicle model, and environmental input from the terrain.

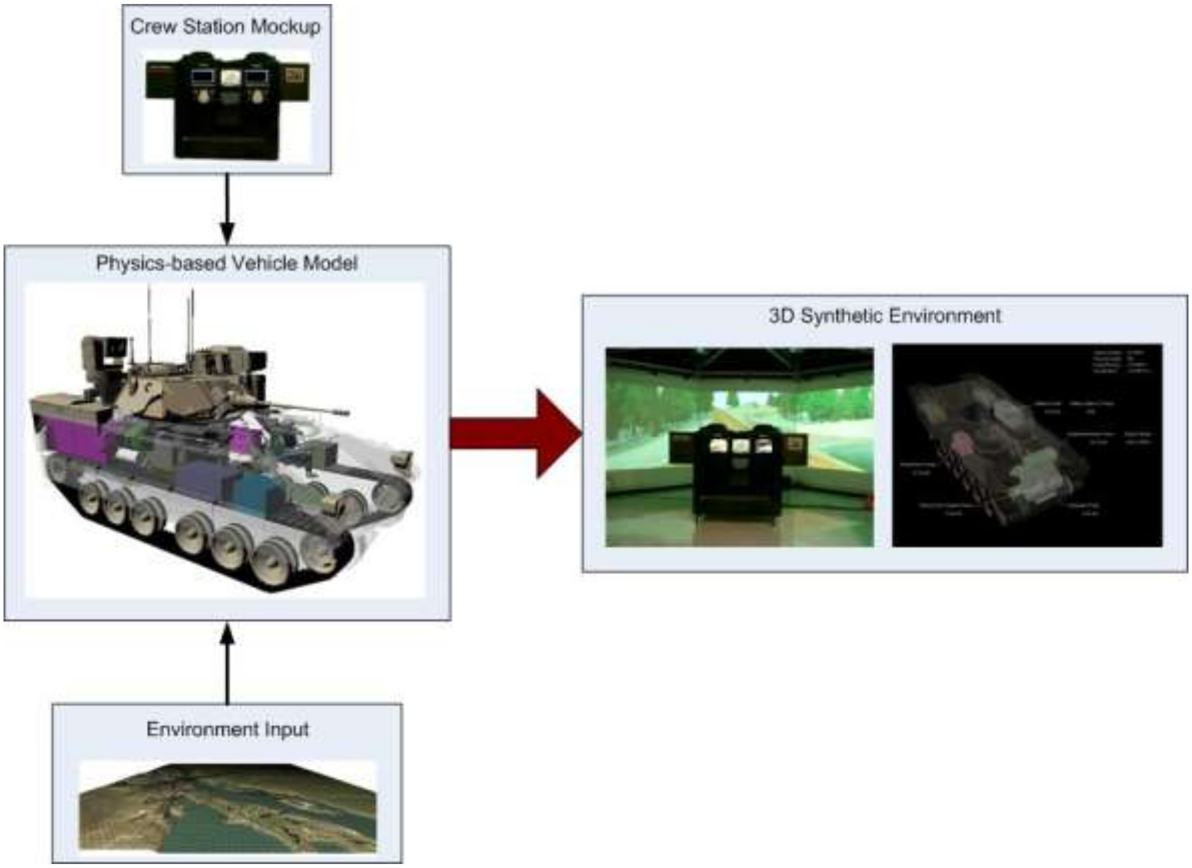


Fig. 2

The user operates the system by generating throttle, steering, and braking commands from within the crew station mockup. These commands, along with environmental input from the terrain database, are then sent to the physics-based vehicle model to predict vehicle performance. Vehicle subsystem and component-level engineering data is sent to the synthetic environment which updates the 3D vehicle model and engineering data visualization screens to display the real-time simulation results for vehicle design and performance analysis.

3 Reconfigurable Crew Station with Synthetic Environment

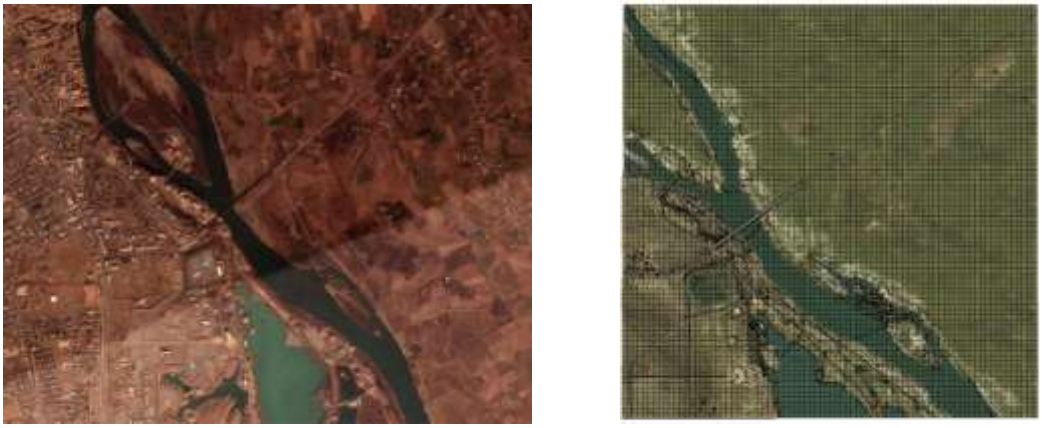
The reconfigurable crew station acts as the intermediary between the operator and the synthetic environment and physics-based model. The crew station is configurable not only in the sense of the external wooden or fiberglass shell and space claims, but it also contains various configurable components which facilitates operator user interaction. These include touch screen displays, vision periscope blocks, control inceptors such as yokes, joysticks, and foot pedals, and control panels with simulated hardware switches.

Fig. 3: Reconfigurable Crew Station

Not only do the interior touch screens display the synthetic environment to simulate a sensor or camera view, but surrounding the crew station mockup is an octagon shaped display surface which 8 projectors project the synthetic environment onto. As a result, an operator within the crew station mockup can use the installed periscopes to view "out-the-window".

Fig. 4: Octagon Shaped Display

The synthetic environment component within the operator-in-the-loop simulator contains image generation software which creates the 3D graphics that construct the artificial world, composing of 3D vehicle and building models as well as terrain databases. It utilizes the widely accepted OpenFlight 3D model format [OpenFlight] which provides the capability of leveraging commercially available vehicle and terrain 3D models as well as the software tools to work with them. Below are pictures of actual satellite imagery of Tikrit, Iraq (LEFT) and of the correlated 3D terrain model (RIGHT) which is used within man-in-the-loop simulator.



Satellite Imagery **Fig. 5** **3D Model**

To simulate vehicle motion, engineering Computer Aided Design (CAD) models are used to import vehicle properties, including geometry, center of gravity, mass, and moment of inertia. The same CAD models are also used for visual presentation in the synthetic environment. BAE Systems owns a process for converting CAD models from Pro-Engineer or Unigraphics formats to the OpenFlight polygonal format [Pro-E][Unigraphics]. The end results are 3D models that physically look identical to the actual vehicle designs and deliver real-time visualization performance. The following figures depict 3D models representative of the Bradley A3 and Paladin.

Fig. 6

4 Physics Based Model

The physics based portion of the simulator is a model of the vehicle in its environment that provides realistic response to operator input in real-time. The model simulates on and off-road mobility, internal power loads, and mission package functions subject to the performance limits of the actual vehicle.

The physics based vehicle performance model architecture was implemented in Matlab/Simulink [MATHWORKS] and uses a modular design. The design features interfaces which divide the simulation into distinct vehicle subsystems while preserving the coupled nature of the numerical solution. Figure 7 shows the interactions of six subsystems which were identified as multibody vehicle, propulsion and power system, suspension, external environment forces, mission equipment, and power loads.

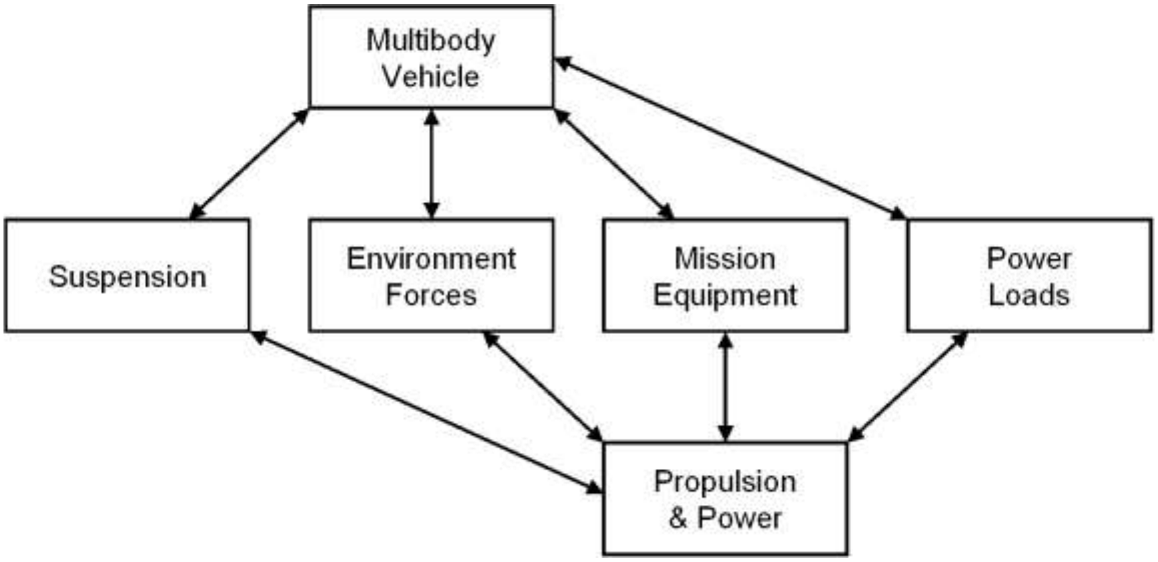


Fig. 7: Physics Model Architecture

The multibody vehicle subsystem encapsulates the dynamic state of the moving vehicle. The multibody subsystem includes the vehicle's articulated bodies such as road arms and turret and interfaces to other subsystems through motions and forces. The propulsion and power subsystem models the hybrid-electric drive powertrain and vehicle electrical power bus. The powertrain interacts with the environment road loads and the power system interfaces with all subsystems which require power. The suspension, mission equipment, and power loads support interfaces to both the multibody vehicle and the propulsion and power subsystems.

Multibody Vehicle Subsystem

The multibody vehicle subsystem simulates the spatial motions of the chassis, road arms, and mission equipment such as turret and gun systems or recovery cranes. The subsystem has a unique design relative to other multibody solutions which are integrated with MATLAB/Simulink. Like most multibody plant models, the subsystem accepts applied forces, prescribed accelerations, and variable mass properties as inputs and provides state dependent kinematic quantities, acceleration kinematics, and constraint forces as outputs. The key difference is that the state dependent kinematic quantities are available before any input is supplied. This allows forces and motions to be based on quantities computed directly from system state within the current function evaluation. The alternative is to avoid "algebraic loops" by introducing delay elements which artificially increases the frequency content of the subsystem interactions.

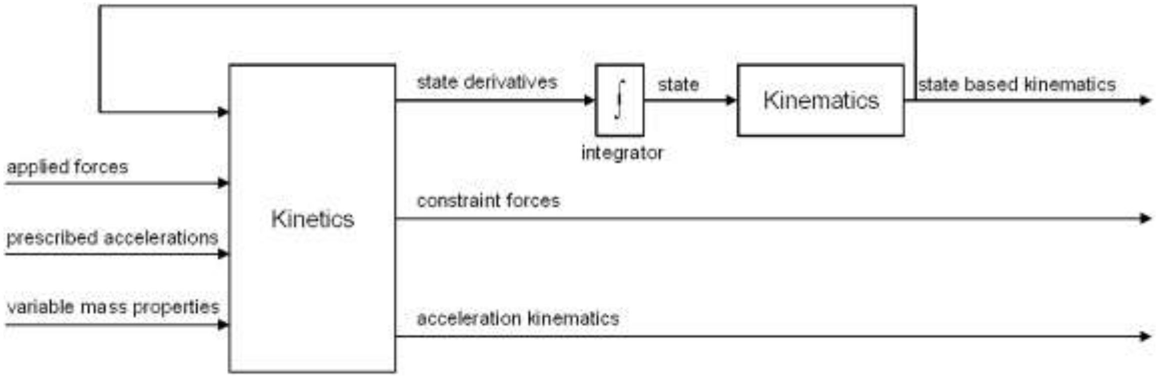


Fig. 8: Multibody Vehicle Model Architecture

The internal architecture of the multibody vehicle subsystem is shown in Figure 8. The Kinetics and Kinematics subsystems have been implemented in AUTOLEV [AUTOLEV] and brought into the Simulink environment as S-functions. AUTOLEV provides a fast symbolically optimized implementation of Kane's Method [Kane] for the solution of multibody problems and the two routines have been setup to read the same configuration file for initialization. The architecture is open to other implementations of multibody solvers however in most cases inclusion of other commercial solvers will require that a sample delay with initial value be inserted on the state based kinematics.

The interaction of multibody subsystems with other subsystems commonly takes the form of state based kinematics measurements such as position and velocities being used to generate applied forces. Passive force based elements such as most suspensions work very easily this way but in other cases it is more natural to reverse the interactions. Allowing a component to have a specified motion and solving for the forces and/or torques which must be applied presents a practical means of modeling many systems. Of particular interest is complex control hardware where the objective and requirements are straight forward. Closing the loop on such systems by evaluating the forces required assures that the response is both physically correct and achievable.

The mission package subsystem interface is also able to prescribe mass parameters which are a part of the chassis. These parameters represent supplies, ammunition, and fuel that may be dynamically consumed during runtime.

External forces (and torques) can also be applied to the model with explicit hooks in place for road loads and weapon recoil which are discussed in other sections. A generic chassis body force and torque applied to the geometric center of the vehicle is also available and serves as an application point for aerodynamic loads and is also reserved for future functions such as vehicle towing, hydrodynamics of fording, collision events, and other interactions.

Propulsion and Power Subsystem

The propulsion and power system of the vehicle are modeled entirely within an existing MATLAB/Simulink toolbox which is described in detail in [Wiederrich]. The emphasis of that work was hybrid-electric drive vehicles but all necessary components for traditional propulsion systems are also present.

Externally the propulsion and power subsystem interfaces to the driver/operator, external forces of ground shear, and power loads on any electric buses. The driver commands are typically steering, accelerator, brake, and gear (PRNDL) and additional or alternate inputs are easily accommodated. The propulsion subsystem manages the degrees of freedom of the running gears and provides speed states to the ground model which resides in the environment forces subsystem. The resistive ground shear forces are computed and applied to the running gears. The power system interfaces to other subsystems by supplying the bus voltage state and accepting a current draw, in this manner it is even possible to import or export electrical power outside of vehicles as necessary for vehicle recovery or service activities.

A vehicle configuration consisting of engine, powertrain, electric bus, and cooling components are all modeled within the subsystem. Each system is uniquely constructed from reusable parametric toolbox elements. Figure 9 (from [Wiederrich]) depicts one such system, a cross shaft steer series hybrid-electric drive tracked vehicle.

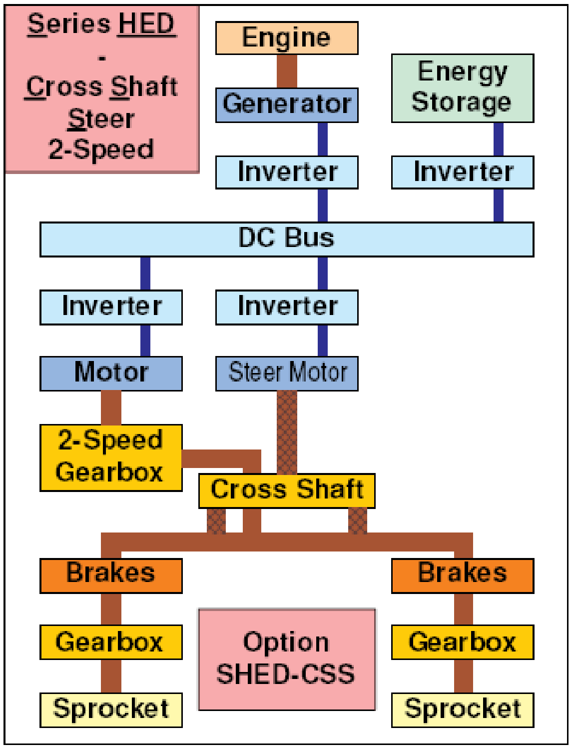


Fig. 9: Example Series Hybrid-Electric Drive with Cross Shaft Steer Mechanism

The powertrain transfers power between the mechanical drive elements and the running gear and may contain any number of gear meshes, differentials, planetary gears, torque converters, range packs, clutches, and brakes. All gear elements compute independent spin and mesh losses (speed and coulomb) which are coupled to the cooling model. It is also possible to include mechanical power take-offs such as pumps and fans and/or additional drive elements at any stage of the powertrain. As an example, the steer motor shown in Fig is connected to the cross shaft gear box in the middle of the powertrain and can provide or regenerate mechanical power based on the desired motion of the vehicle.

The electric bus or buses on a vehicle connect motor/generators, alternators, dissipaters, batteries and other storage devices, electric pumps or fans, and all other electric loads. The bus is modeled with a lumped capacitance enabling voltage to be provided as a state with the summation of all current draws determining the dynamic behavior. The addition of a propulsion controller which is also available as parametric modules is commonly required for hybrid-electric systems to prevent large mobility loads from adversely affecting the stability of the bus voltage. The detailed electrical interactions of the subsystems commonly results in a requirement for temporal resolution on the order of kHz with a third order ODE integrator.

Engines and electric motors are provided at varying levels of fidelity. At a minimum an engine requires a rotary inertia, maximum power versus speed and efficiency (fuel consumption) data. Similarly an electric motor/generator requires the same information with efficiency data relating to the conversion between electrical and mechanical powers. The most basic engine and motor models are dynamic in that they track a continuous speed state but allow discontinuous jumps in power setting (limited by the power versus speed profile). Higher fidelity representations contain characteristics such as turbo lag and stator dynamics and can be used when data is available.

Cooling systems collect power losses at each element and apply them to thermal masses (and exhaust in the case of engines). The thermal masses are cooled by fluid loops and internal air which is moved by pumps and fans which may be electrically or mechanically driven. Heat is transferred between hot and cold loops and external air by exchanger elements.

Hydraulic power for accessories, mobility, and energy storage are also available within the propulsion and power system architecture and functions in a manner consistent with electrical and mechanical pumps and motors.

Suspension Subsystem

The suspension subsystem models the dynamic response of the suspension elements to the terrain. Commonly the suspension consists of forcing elements such as torsion bars, springs, dampers, and hydraulic actuators which use position and velocity measurements to compute applied forces that feed back into the multibody vehicle dynamics solver. Suspension subsystem models which interact through applied forces are usually represented by spring and damping curves (Simulink look-up tables), but this interface also applies to more complex semi-active and active suspension mechanisms. An interface to the propulsion and power subsystem is also made available for configurations which may require connections to electrical power for active elements or instrumentation and/or connections to the cooling system.

The bump stops on many suspensions are very stiff and can cause a fixed step integrator to fail. To overcome this numerical limitation one may choose either to limit the bump stop stiffness or implement prescribed motions of road arms when the stops are in contact. Limiting the bump stop stiffness is the simplest alternative and provides no approximations in routine driving conditions. Identifying the cutoff stiffness value involves solving for stiffness value of the suspension such that the damped frequency response does not exceed one half of the time step frequency. In practice one can also drive the vehicle model aggressively using a variable step integrator (refining step size based on estimated error) and extract the stiffness and damping values just before the desired integration step threshold is exceeded.

An alternative to limiting the suspension stiffness is to model the bump stop objective. In this case the AUTOLEV model is adjusted to include variable suspension motion regimes. In AUTOLEV terms, placing a specified variable on/off switch (one or zero) with additional terms in the partial velocity and kinematic differential equations will suffice. In intervals where the bump stop is encountered the suspension is prescribed via a cubic function (exactly integrated by a third order integrator) to return to the boundary of the bump stop and to rest relative to the chassis.

In the case of active or semi-active suspensions it may also be possible to model the control objective through specified motions but this a topic for future research.

Environment Forces Subsystem

The environment forces subsystem encapsulates the computation of forces which are developed through contact with the terrain and other external influences. The subsystem interfaces to the multibody vehicle by receiving state based measurements such as chassis and wheel locations and returns forces which are applied to individual bodies. The environment forces also require an interface to the propulsion and power subsystem which takes running gear speed states and responds with a resistance force.

Ground force interactions are computed using the steady state relationships found in Wong [Wong]. Applying the steady state ground force relationships to dynamic interaction is a common procedure in real-time simulations and is outlined in several publications, such as that of Romano [Romano]. The contact model used differs in subtle ways from Romano particularly at low speeds where the implementation takes advantage of the high frequency integrator required for the propulsion and power subsystem. The force model is allowed to naturally degenerate to stiff coulomb type interactions that do not result in sliding on sloped terrains, removing the need for additional approximations under these conditions as cited by others.

In the case of tracked vehicles, only the terrain normal restoring forces are applied to the suspension (road wheels, road arms, springs and dampers). Longitudinal ground shear loads are summed and supplied as left and right track resistive forces to the propulsion system. The individual ground shear loads are applied to the chassis body at points instantaneously coincident with the ground contact (which are not in general static or physical points on the body). The mass of the track is commonly lumped in as part of the chassis mass in the multibody model and as sprocket inertia in the propulsion system but other alternatives are possible.

The normal load, sinkage, and soil type are also used to determine any applied rolling resistance features of the vehicle and combined with the ground resistive forces that are provided to the propulsion system.

A simple aerodynamic model based on the drag coefficient of the front and sides of the vehicle and the wind if any is used to apply drag forces and torques through force/torque handle the geometric center of the vehicle. The same force handle is intended to be used for more sophisticated external interactions such as collisions and towing forces which are intended to be implemented in this subsystem.

Mission Equipment Subsystem

The mission equipment on a military vehicle is the portion which distinguishes it from a strict mobility platform. Mission packages often include articulated turrets and guns but there is also a wide variety of combat engineering and re-supply vehicles with plows, rollers, cranes, booms, towing rigs, ramps, bridges, export power generation, equipment and supply stowage, and potable water generation and storage. Equipment containing articulated parts and variable masses involve coupling to the multibody vehicle subsystem.

Depending on the objective of the design activity supported by real-time simulation, the representation of the mission package can vary significantly. If one is interested in the performance of weapon stabilization algorithms or the performance of a particular hydraulic mechanism as for a towing lift mechanism, then a complete representation of the equipment down to control algorithms would be expected. Implementation of this type of detailed model follows the basic conventions already laid out in the multibody vehicle subsystem and propulsion and power subsystem interfaces.

On the other hand, if the design objective is to asses the system performance as from conceptual design requirements, then the only alternative is to modeling the performance objective of the equipment. Relating this methodology to the earlier example of weapon system stabilization, the control objective tracking characteristics would be modeled as prescribed multibody motions allowing the operator to asses the quality of the requirements in a test on virtual terrain.

Objective models of articulated equipment have been further enhanced to include actuator rate and force limits which relax the specified motion constraint and identify areas where the system is unable to meet the requirements.

An objective model of a gun turret drive has been implemented which features a second order system specifications for tracking accuracy, position and slew rate limits, torque limits and several modes of operation including auto target tracking and inertial stabilization. Weapon firing also places a recoil force on the gun which is computed by applying an impulse (step change in velocity) to a second order mass spring damper system of appropriate characteristics.

The mission package is also responsible for tracking fuel usage and weight of supplies. The propulsion and power system engine components draw fuel and an external interface is provided for re-fueling on terrain. As the mission package supplies and fuel are used, the mass of a variable element within the multibody vehicle subsystem is updated to reflect a lighter vehicle.

Power Loads

The power load system such as lights and sensors is modeled physically as power draws on the electrical system using the interface described in the propulsion and power subsystem. It is a Matlab Simulink model with code generation via Real-Time Workshop. Initial modeling consisted of a nodal analysis (nodal-voltage-analysis). In order to achieve real time performance, modeling approximations consistent with intended use were made. For the most part, LRU loads were approximated by real impedances, estimated from measurement of steady-state power consumption. Since the intended system was DC, inductive voltages were neglected.

Simulink components were made of three categories: sources, sinks, and "buses". Sources, as a minimum, have voltages as outputs, and current as input. Sinks, likewise, have current as output and voltage as input. "Buses", provide the interface of sources and sinks. Thus, as a minimum, buses have input voltages and output currents from all the connected sources, as well as input currents and output voltages to all the connected sinks. All components may have additional signal or state lines as input or output. Special care was necessary for items which may behave as both a source and sink (i.e. charged vs. discharged batteries) to avoid algebraic loops.

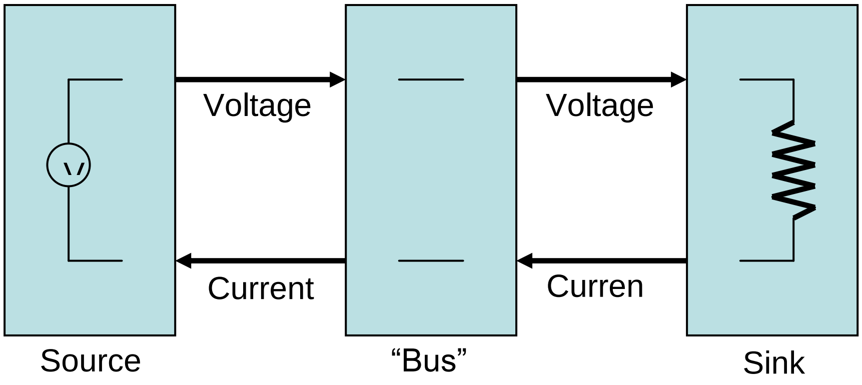


Fig. 10

Sources and sinks can be almost anything from simple/ideal to complex/realistic. These blocks may have there own state variables, or be coupled via signals to external inputs or co-simulations (i.e. generator-engine coupling). Inductive loads could be modeled, but are generally avoided since they induce a very small time step. “Buses” contain capacitive elements which maybe tuned to best represent in-situ systems. This capacitance, consequentially, is what will usually dictate the necessary time step (rc time). To provide real time performance as well as high-fidelity may require compromise. Thus, knowing the time scale of desired transient behavior to be represented a priori helps.

5 Man-In-The-Loop Design

To facilitate the vehicle performance design and analysis, the real-time man-in-the-loop simulator environment implemented a comprehensive visualization system, which includes 3D animation of vehicle platform performance and XY-Plot of engineering data.

The 3D animation depicts the major subsystems of the Hybrid Electrical Drive (HED), including battery, fan, energy dissipater, engine, and Traction Drive System (TDS). These graphical models (see Fig. 11) dynamically change color to illustrate current power generation and consumption. A red colored (negative value) 3D model represents a subsystem that is consuming power, a green (positive value) model is generating power, and grey is neither consuming nor generating. In addition, text overlays are positioned next to these 3D graphical representations which also dynamically update to display the specific power levels in operation. The 2D XY plot graphs the history of the key subsystem simulation results for engineering performance analysis.

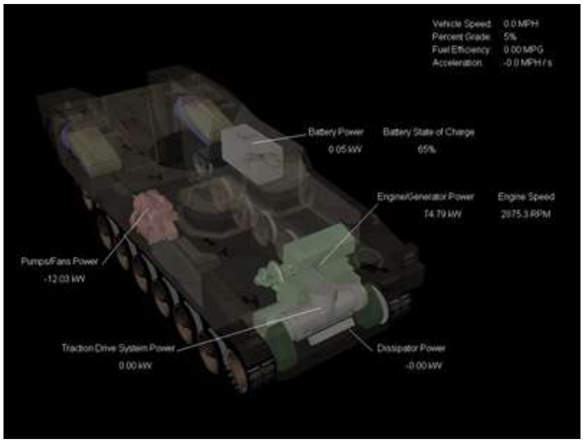


Fig. 11: Key Components

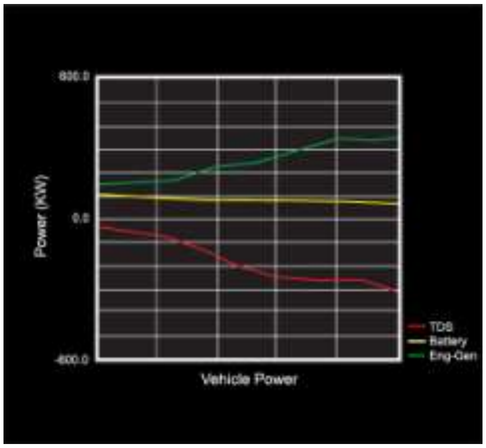


Fig. 12: Acceleration

The simulator allows engineers to perform real-time simulation with the capability of human-machine interface to study vehicle performance, including acceleration, power balancing, and vehicle maneuverability on various ground profiles to perform different missions, including vehicle forwarding, stopping, turning, and pivoting. While a user begins accelerating the vehicle from within the crew station mockup, the engineering displays would then depict a green engine and batteries which would be supplying power to the TDS, which in turn would be red. Figure 12 shows the engineering data of engine and TDS.

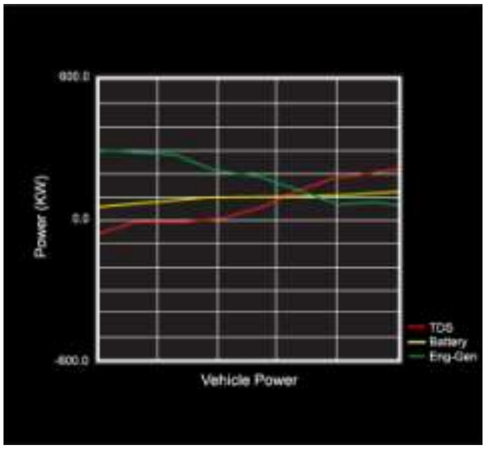


Fig. 13: Deceleration

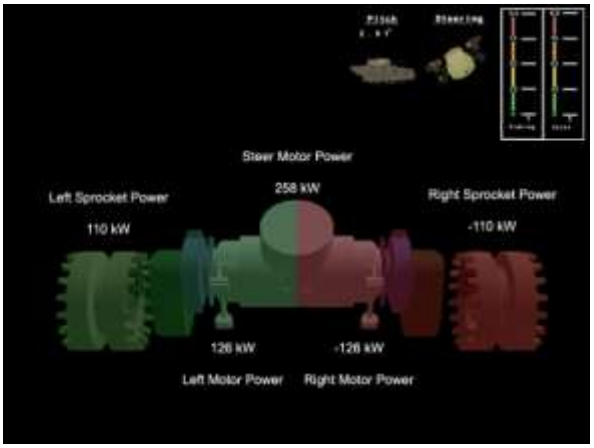


Fig. 14: Turning

As the driver decelerates, the engine and batteries would become red and the TDS green, as it regenerates energy from braking back into the batteries. Any lost energy that cannot be regenerated would be sent out through the dissipater and figure 13 shows the simulation results. And finally, in the case of a driver accelerating through a turn, because this vehicle model represents a skid steer vehicle with independent sprocket motors, the engineering display would show the power flowing from one side to another (see Fig. 14). This illustrates the energy levels as one side of the tracked vehicle would be braking, and the other accelerating to produce this skid-steer effect. From these engineering data displays, engineers can dynamically operate unique mission profiles to study platform, subsystem, and component-level vehicle performance.

The simulator also implemented a data recording capability. In addition to studying various mission profiles, engineers and designers can also quickly modify vehicle configurations such as weight and compare performance of multiple design simulation results head to head by utilizing this data recording and playback capabilities.

6 Summary

The man in the loop simulator provides an ideal environment for vehicle design and performance studies. The simulator provides the ability to easily compare the performance of different component or subsystem designs or the ability to do head-to-head comparisons of different components within the same design. The simulator facilitates the ability to quickly experiment with component sizes to determine the optimum configuration for the current design and can use it to develop the controller for the system to optimize its performance. And finally, the man-in-the-loop aspect allows engineers to test the simulated vehicle over a much larger range of driving conditions and scenarios as opposed to fixed test cases. Man-in-the-loop simulation provides a flexible environment for vehicle performance analysis and design. It reduces both the vehicle development cost and schedule risk.

An additional benefit is that an actual customer can operate a simulated version of their vehicle prior to any hardware prototypes being built, and can provide valuable feedback that aids in the iterative design process. Human Factor Engineering (HFE) evaluations can utilize the man-in-the-loop simulator to create a more soldier-centric design. Through ergonomic evaluations, HFEs can place test participants within a mission scenario and evaluate their performance within the reconfigurable simulator. For example, a participant can drive a certain mission profile using multiple crew station configurations that differ by display sizes, simulate sensor locations, or test various yoke and joystick configurations. In addition, hardware components and subsystems can be evaluated not only to verify that they meet performance specifications, but also to verify they maximize soldier performance during a mission scenario.

7 References

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[Kane] Kane, T.R. and Levinson, D.A., “Dynamics: Theory and Application”, McGraw-Hill, New York, 1985.

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[OpenFlight] OpenfFlight is a registered trademark of Presagis Inc.

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