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HARDWARE-IN-THE-LOOP PLANT MODELING IN SUPPORT OF THE US ARMY'S COMMON POWERTRAIN CONTROLLER DEVELOPMENT

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ABSTRACT

Developing and deploying new powertrain controls software/hardware rapidly, efficiently, effectively, and with low technical risk is a common goal for many organizations, including the US Army. To help ensure these goals are met, the US Army leverages a variety of sophisticated engineering techniques including Hardware-in-the-Loop (HIL) methodology. This paper covers the benefits and implementation of HIL/SIL methodology, especially as it applies to the US Army's neXtECU common powertrain controller platform. It then expands on this background by providing an example in which high-fidelity plant models were developed of the M1A2 Abrams's AGT1500 gas turbine, drivetrain, and vehicle dynamics and deployed on an ETAS LABCAR setup as part of a HIL application.

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1. INTRODUCTION

To maintain a high degree of excellence in support of its fighting force, the US Army continually seeks improved technologies and technical approaches. One recent introduction is a common powertrain controller platform, termed the neXtECU, which has been developed internally by the Real Time Control Systems (RTCS) group within the US Army's Ground Vehicle Systems Center (GVSC).

The neXtECU is a highly capable and open (to the US Army) platform consisting of controller hardware, designed for the rigors of military applications, coupled with a fully featured embedded controls development tool chain. It is intended both as a retrofit for existing powertrain platforms to enhance system performance and capabilities, as well as in new vehicle and powertrain platforms to accelerate development times. This accelerated development capability ensures these systems keep pace with the rapidly evolving environment/requirements which have been placed on military ground vehicles. One recent retrofit discussed by Yancone et al. [1] is application of the neXtECU to the M88 recovery

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DISTRIBUTION A. Approved for public release; distribution unlimited. OPSEC # 4167 vehicle platform where the original engine featuring mechanical fuel injection was upgraded to a modern electronically controlled fuel injection system resulting in improved performance, efficiency, and durability while also reducing lifecycle cost. Another neXtECU application under evaluation is the control of the AGT1500 gas turbine in the Abrams M1A2 platform.

To accelerate the application of the neXtECU to the Abrams powertrain, and to ensure technical success, RTCS included Hardware-in-the-Loop (HIL) methodology as part of their overall development approach. HIL architecture, in this application, consisted of the neXtECU controller connected by means of a standard wiring harness to I/O emulation hardware which replicates the AGT1500 and driver inputs. Running on the emulator hardware is real-time high-fidelity plant model of the Abrams's AGT1500, drivetrain, and vehicle dynamics which takes in commands from the neXtECU, simulates how the entire Abrams's powertrain and vehicle would respond, and outputs signals to emulated sensors which are then read by the neXtECU through the wiring harness. In effect the neXtECU is spoofed into believing it is controlling a physical AGT1500, when actually it is in a carefully controlled environment which can be highly beneficial for controller development.

As part of this program, Czero developed the high-fidelity plant models of the Abrams's powertrain/ vehicle dynamics and implemented it on the HIL hardware. This paper briefly covers the neXtECU platform, HIL/SIL methodology and benefits of this approach, and finally the Abrams HIL model.

2. neXtECU CONTROLLER

The neXtECU is at the core of the US Army's common powertrain controller platform. It is a state-of-the-art embedded controller designed with the goal that a single highly capable and validated hardware platform can be applied across a wide range of military vehicles. The only changes required between these diverse applications would be to the software loaded onto the ECU (Engine Control Unit), not to the hardware itself. The neXtECU is intended as a technology enabler that is capable of integrating current and future generations of vehicle control systems into both the US Army's existing fleet of vehicles as part of modernization efforts, and as original equipment in both prototype and production vehicles.

Some of the advanced systems the neXtECU is designed to control include electrified and hybridized powertrains, electrified sub-systems (e.g. steering, pumps, fans, PTOs), smart cooling systems, high performance and power dense prime movers such as opposed piston designs, and high range multi-speed transmissions. It can control these advanced systems, in part, due to the large amount of I/O it contains relative to comparable military grade controllers.

The neXtECU is designed specifically to meet the rigors of military applications in ways standard ECUs are not. Some of these enhancements include radiation hardening, nuclear event detection and protection circuitry, mil-spec connectors, and the ability to pass a full suite of military tests. An earlier development version of the neXtECU, with select applications, is shown in Figure 1.

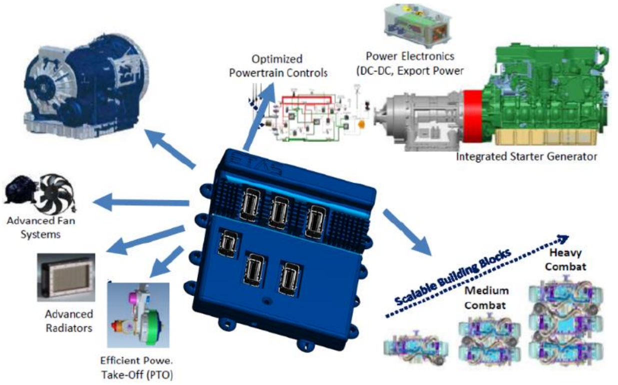

Figure 1: neXtECU with Select Applications [1]

The neXtECU hardware is only a portion of the common powertrain controller platform; the other essential element is the software used to develop the controls code, as well as the software running on the ECU. This code leverages both standard ECU code, and automotive industry standard coding practices, to ensure robustness and interoperability.

Using a common powertrain controller platform provides multiple benefits to the US Army; some of these advantages include:

- Shortened development time by building on an existing system with established methodologies and code reuse
- Reduced cost and technical/schedule risk by utilizing a known and validated software/ hardware platform rather than developing a custom solution for every application
- Owned by the US Army which ensures the software is both fully open for initial development, and in the future for upgrades and enhancements
- Increased flexibility for incorporating additional systems and features over a vehicle platform's lifecycle
- More I/O than a standard automotive controller and designed specifically for military applications
- Interoperability between vehicle platforms as hardware can be moved from one application to another by simply updating the controls code

GVSC's Real Time Control Systems group, along with ETAS and Hybrid Controls, has developed and applied the neXtECU to a range of powertrain applications. Their capabilities range from hardware and detailed controller development to implementation and final validation on vehicle platforms. Throughout the controller development and validation process, RTCS utilizes a number of sophisticated tools and methodologies to accelerate development and ensure a robust and highly effective final system. One of the powerful tools/ methodologies RTCS employs in support of ECU development is hardware-in-the-loop.

3. HARDWARE/SOFTWARE-IN-THE-LOOP

3.1. HIL Methodology

Hardware-in-the-loop, at a fundamental level, refers to having components of primary interest physically present, while supporting components are simulated. Multiple HIL architectures exist, including those where the components of primary interest are the powertrain hardware coupled to electric units serving as engine and vehicle dynamics simulators. The approach used by RTCS for controller development, however, consists of the neXtECU as the component of interest physically present connected to specialized HIL hardware by means of a standard wiring harness. The HIL hardware consists of an I/O layer capable of sensing any type of analog or digital command signal output by the ECU, and replicating any type of sensor output which the ECU senses through the harness. This I/O layer is coupled to real-time software running a dynamic simulation model of the powertrain being controlled by the ECU. This plant model simulates how a physical powertrain would react to the control signals output by the ECU, and feeds back the appropriate sensor outputs to the ECU through the I/O layer. Figure 2 shows this general HIL topology.

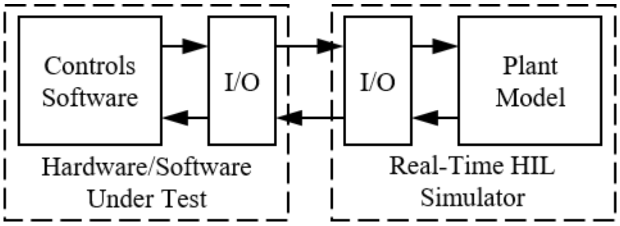

Figure 2: HIL Topology

While utilizing HIL systems as part of the control system development process has become standard practice in many commercial sectors, it is not strictly required. To meet demanding timelines, controls development often begins while the powertrain hardware is still being designed, and is expected to be ready for testing on the powertrain hardware as soon as the hardware is complete.

Without HIL (or SIL, discussed later) a more conventional controller development process may require that the entire controls code be initially developed and deployed on the controls hardware completely independent of the powertrain platform. The controller would then be connected to the actual powertrain hardware for initial debug, testing, tuning, and final validation with the hope that this process proceeds smoothly and rapidly without damaging the prototype powertrain hardware (which is likely still under development).

Conversely, when utilizing HIL methodology, a dynamic plant model of the powertrain can be developed at the onset of the project and serve as a stand-in for the physical powertrain in the controller development process. This enables the powertrain controller to go through much of the initial debug, testing, tuning, and validation process before ever being connected to the physical powertrain. Once the powertrain is ready, the previously validated controls software/hardware can be connected to the powertrain with increased confidence and ideally requiring only some minor final tuning and validation before being deployed in the final application.

An essential aspect of HIL systems is that all components emulating physical hardware operate in “real-time”. While no rigorous definition exists, for these applications real-time essentially means that the HIL systems do not present an increased or decreased time response relative to the physical systems they are emulating which could be detected by the hardware under test. This is necessary both to properly evaluate/tune the control algorithms, and to ensure the controls software/hardware, which runs at a fixed rate, does not run into any issues when operating under full capacity such as runtime violations. To achieve real-time operation the HIL system must typically operate, at a minimum, at the same rate as the controller (though the plant model may need to be simulated at a higher rate to accurately capture relevant dynamics). While this rate is unlikely to pose issues for the I/O interface layer, it can present challenges for the plant model as discussed in subsequent sections.

3.2. SIL Methodology

A closely related approach to Hardware-in-the-Loop is Software-in-the-Loop (SIL). They are similar in that both approaches contain the controller and plant model of the system being controlled. In HIL systems (for the controller centric approach) the controls software is deployed on physical controls hardware connected to a real-time HIL platform running the plant model. Conversely SIL does away with all physical hardware and runs the controls software and dynamic plant model in a co-simulation mode. One example of SIL topology is shown in Figure 3.

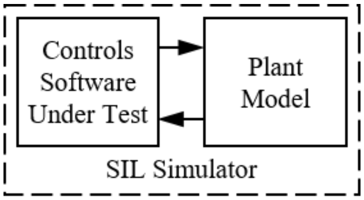

Figure 3: SIL Topology

SIL can be thought of as a more fundamental approach than HIL. While SIL (in control system development) focuses on the interaction between control system and the plant model, HIL expands this by placing the controls code on physical controls hardware interacting with a plant model running in real-time on a HIL system. While this type of HIL methodology enables valuable testing and validation of the controls hardware and software/hardware combination under more real-world conditions, it is somewhat less versatile than the SIL approach.

SIL has several benefits relative to HIL including not requiring physical hardware and being able to be run on any computer with the appropriate software. This means that the SIL development architecture can be deployed on many computers without specialized hardware reducing costs and speeding development time (if access to HIL hardware is a bottleneck). SIL also does not require the plant model or controller to be run in real-time. This potentially reduces the plant model’s development effort and enables increased model fidelity (if computational burden is a limiting factor in model fidelity). Finally SIL and HIL are not mutually exclusive, the same plant models may be used in both SIL and HIL applications as part of a cohesive development environment.

A primary drawback to utilizing SIL over HIL is that SIL does not evaluate the control software running on the actual controller hardware. This validation is important as control code must run in real-time and SIL may not capture overload events where the controls hardware is unable to provide sufficient computational power.

3.3. Benefits of HIL/SIL

There are many significant advantages to utilizing HIL/SIL methodology as part of a controls system development program. Relative to project management HIL/SIL methodology can reduce technical, schedule, and budgetary risks. Technical risks can be reduced, in part, by:

- Developing, tuning, and validating the controls system before connecting it to the physical powertrain hardware. Depending on a powertrain's failure modes, there is a very real risk of damaging the hardware if it is controlled incorrectly. The potential for damage to the powertrain due to controller error is made more likely as the powertrain's complexity is increased
- Controller based fault detection and safety system, which protect powertrain hardware, can be tested and validated virtually before being relied on to prevent hardware damage
- "Relearning" the original system designer's design intent and "tribal knowledge" when these personnel are no longer available before applying these control strategies to the physical powertrain. This is especially pertinent to military powertrains which may have lifecycles stretching over many decades with the platforms owned by multiple companies

Scheduling risk can also be mitigated utilizing HIL/SIL methodology by:

- Reducing the risk of damage to the prototype powertrain hardware which may result in a schedule delay
- Controller validation can be begun before the powertrain hardware is ready for testing providing more time to complete the work. If controller development is the critical path, the overall program duration can be shortened
- By beginning controller validation sooner, any potential issues are likely to be identified earlier in the project timeline enabling corrective actions to be applied
- If access to powertrain hardware is limited (especially if multiple groups require access), it is possible to duplicate the powertrain plant model onto multiple HIL systems to enable parallel controls development and validation of multiple sub-systems

Mitigation of risks to project cost is principally related to reducing both technical and scheduling risks as both areas can contribute significantly to budget overruns.

HIL/SIL methodology offers many other benefits in the controller development process as well. Relative to the control's development process HIL/SIL methodology enables:

- Evaluating how the system responds outside of the normal safe operating envelope without having to place physical hardware in potentially damaging situations (to verify safety system without damaging equipment)
- Inject disturbances, sensor errors, actuator faults, etc. to evaluate the control system's response and fault tolerance
- Detect potential failure modes
- Develop and validate new control strategies
- Create automated and comprehensive testing procedures for code validation (increasing repeatability/robustness and reducing development time/cost through automation)

- Debug “hard to find” field issues by using the HIL capability to step through the controller and plant model code to pin-point the problem

Thus far the focus of HIL/SIL has been on employing these methodologies to support the ECU development process. Yet the combination of a controller with a high-fidelity plant model can also be a powerful tool in a vehicle platform’s overall development and lifecycle management. A few examples of leverage HIL/SIL methodology outside of controller development include:

- Quickly evaluate the impact of upgrading a platform with new components, such as a new motor technology in a hybrid electric vehicle
- Human factor development (UI development, ease of operation, etc.) and operator training
- Automated end-of-line testing on all manufactured controllers to ensure proper operation (e.g. validate all hardware components and I/O functions properly)
- Replicate field failures virtually as part of a failure mode root cause analysis to speed the process and gather information otherwise not readily available
- Ability to capture “road scenarios” which can be replayed on the HIL system. This can support both failure mode analysis as well as in validating new software releases
- Creating a virtual lab to be used by multiple groups. The plant models can be used both as part of the HIL/SIL system, and independently by other development engineers
- The HIL plant model can easily be extended to other vehicles reducing development time. Similarly, the dynamic powertrain models frequently developed as part of analysis lead design efforts can often be ported into HIL/SIL applications

3.4. Plant Modeling

At the core of HIL/SIL methodology are dynamic plant models which simulate the physics of the emulated hardware. Often a principle challenge in developing plant models for HIL systems is that they must run in real-time. Achieving real-time operation is based on several factors, including:

- Controller rate (typically minimum rate plant model can be simulated at to prevent time based delays)
- Simulation rate required to accurately capture relevant physics within the plant model. A faster rate than is used by the controller may be necessary to maintain suitable accuracy
- Computational power of the HIL hardware. Higher performance HIL hardware can execute a single time step more quickly enabling either more complex systems to be simulated, or less complex systems to be simulated with reduced effort required to optimize computational performance

Once the minimum rate required to both maintain real-time operation and capture the relevant physics is established, the initial plant model is typically run at that rate on the HIL hardware to determine computational performance. HIL systems will often provide feedback on processor load and any real-time violations which help inform model development. Real-time violations are an important metric as they indicate the plant model is not consistently running in real-time and the cause of these violations must be identified and resolved.

The processor load should also be evaluated as it provides feedback regarding how much processing capacity is being used by the HIL system. Preferably the processor capacity will be maintained at low to moderate capacity with some headroom (e.g. 30%) remaining. This headroom helps prevent real-time violations in case of short duration high computational expense events, and also provides room for additional physics or sub-systems which may need to be incorporated into the plant model at a later date.

One challenge faced in achieving a high level of model accuracy is that many HIL systems require the plant modes to be simulated using a fixed time step solver to help ensure consistency. Conversely, many off-line dynamic system modeling tools allow variable time step solvers to be used which dynamically vary the size of the integration time step based on system physics. When minimal changes are occurring these variable time step solvers takes larger time step to simulate the system more quickly, while taking much smaller time steps to resolve periods of rapidly changing system dynamics. Variable time step solvers are especially useful in efficiently modeling stiff systems such as hydraulics in which a small input change (e.g. flow into a volume) can result in a large state (output) change (e.g. pressure in that volume).

A range of strategies have been developed to enable dynamic models to run at fixed time steps suitable for real-time operation. One common approach is to reduce model stiffness such that the change in a model's states per time step is reduced, for example by increasing the size/capacitance of a volume. While highly effective, changing model stiffness influences system dynamics and must be done carefully to ensure the system's transient response is not altered to an unacceptable level. A related approach is to lump together volumes which may otherwise be discretized to capture effects such as wave dynamics. While the effects would no longer be captured, they may not strongly influence the overall system dynamics and could be considered an acceptable simplification.

A corollary to reducing model stiffness (change in state relative to change in input) is to reduce the rate at which inputs change. For example a 1st order transfer function may be used to slow the rate at which a valve opens, rather than permitting an instantaneous change from closed to open in a single time step. As a result, the simulation is given multiple time steps to respond to the change in valve flow lessening the change in state per time step thereby increasing model stability. The objective both of decreasing a system's stiffness, and reducing the rate at which inputs change, is to minimize numerical instabilities which may otherwise prevent the step size required to achieve real-time operation from being realized.

In addition to modifying physics within the model to achieve stability, changes in the numerical solver often prove beneficial. Plant models can typically be simulated using a range of ODE solvers. While higher order solvers typically incur increased computational burden, they may also permit larger time steps to be employed reducing the overall simulation time while providing increased stability. Further implicit solvers, though more computationally expensive than explicit solvers, are more stable and may permit further increases in step size.

4. ABRAMS HIL DEVELOPMENT

One recent application under exploration by RTCS for the neXtECU common powertrain controller platform is to control the Honeywell AGT1500 gas turbine used as the prime mover in the Abrams M1A2 main battle tank. Due to the complexity of gas turbines and related control systems, this is an ideal application for leveraging HIL methodology as part of the controller development process. As part of the AGT1500 neXtECU exploration process, RTCS and Czero developed high-fidelity plant models of the AGT1500 gas turbine and the Abrams M1A2 drivetrain/ vehicle dynamics and deployed it on several of RTCS's ETAS LABCAR HIL systems. This HIL system was used to develop and successfully validate controls software for the neXtECU capable of controlling the AGT1500 gas turbine. Further this HIL configuration is available and capable of supporting other efforts on the Abrams platform.

4.1. M1A2 Abrams

The M1A2 Abrams is the US Army's main battle tank (Figure 4). Development of the original Abrams variant began in the early 70's before entering service in 1980. Since then multiple variants have been developed and upgraded requiring more advanced control systems.

Figure 4: Abrams M1A2 [2]

The Abrams is powered by a Honeywell AGT1500 gas turbine (Figure 5). This automotive gas turbine (AGT) produces 1500 shaft horsepower and was originally developed by Lycoming for use in ground-based military vehicles. It is a turboshaft gas turbine which propels the vehicle through rotational shaft power rather than jet thrust. The turbine's output shaft is connected directly to the transmission module's input forming the primary power pack.

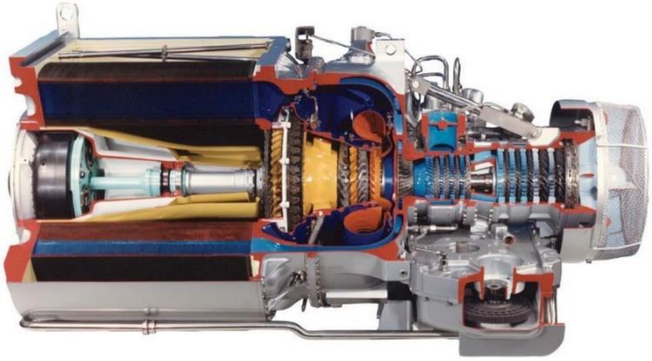

Figure 5: Honeywell AGT1500 Gas Turbine [3]

Connected directly to the gas turbine is an Allison X1100-3B1 transmission module (Figure 6). This subsystem consists of an automatic transmission with torque converter and four forward/ two reverse speed ranges, a cross-drive steering mechanism to turn the vehicle, foundation brakes, and final drive.

Figure 6: Allison X1100-3B1 Transmission Module [4]

4.2. HIL Plant Model Development and Validation

The Abrams HIL system was created primarily to support development and validation of the neXtECU software/hardware platform for use in controlling the AGT1500 gas turbine. To support this effort, a high-fidelity plant model of the gas turbine was developed and validated. To provide more realistic output loads and transients (especially those which may influence control requirements) for the gas turbine, a plant model of the Abrams's drivetrain and vehicle dynamics was also created.

AGT1500 Gas Turbine

The purpose of a HIL system plays a major role in determining what type and level of fidelity of plant model is appropriate, in this case the purpose was to develop and validate controls software/hardware for controlling the gas turbine. As such the appropriate level of fidelity for this application was a fully predictive and physics-based approach (rather than, for example, utilizing a surrogate model based on measurement data as may be sufficient in some other HIL applications). By utilizing a physics-based modeling approach the HIL system can predict the gas turbine's states and transient response to a range of conditions much broader than would otherwise be available in test data. Importantly the physics-based model can predict the system's response outside of the safe operating envelope (e.g. over speed/temperature conditions) which are essential for validating the controller's safety routines.

RTCS's ETAS LABCAR HIL system can integrate plant models built in a range of programming languages into its real-time system, one of them being MathWorks's MATLAB Simulink. Simulink is a widely used graphical programming language well suited for both the development of plant models and control systems. It is also well suited for running in co-simulation modes as part of a SIL strategy and was thus selected to develop the plant models.

The plant model's overall structure closely mirrors the gas turbine's physical arrangement. A simplified process flow diagram of the AGT1500 is shown in Figure 7. The low and high pressure gas generators are each comprised of multi-stage axial flow compressors coupled to multi-stage axial flow turbines connected by concentric shafts allowing independent motion of the low and high pressure generators with the turbines powering their respective compressors. Ambient air is drawn into the turbine and compressed initially by the low pressure compressor (LPC). This compressed air then flows into the high pressure compressor (HPC) and is further compressed. This now fully pressurized gas flows through the recuperator, a type of gas/gas heat exchanger, to recover heat otherwise lost in the exhaust stream as a method for improving system performance and efficiency. The flow then enters the combustor where fuel is added to the gas stream and combusted, further heating the gas and providing the energy input into the gas turbine. The gas stream is then sequentially expanded through the high and low pressure turbines (HPT and LPT) providing power to their respective compressors. The remaining enthalpy in the gas stream is available to produce useful work, some of which is extracted by expanding across the power turbine (PT) which is connected to the AGT1500's output shaft.

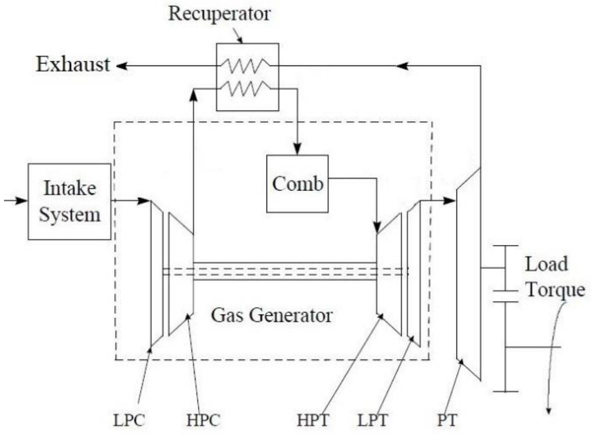

Figure 7: Honeywell AGT1500 Schematic [5]

The AGT1500 HIL model was constructed using a lumped parameter modeling approach. That is the system was broken down into a series of relatively large elements, such as the flow passage between LPC and HPC. These volumes were treated as a single element rather than being discretized into smaller individual volumes as would occur in CFD. Due to the real-time requirement for this model, the system was split into as large of sections as possible while still capturing the desired physics.

For the gas flow path the system was split into two types of elements: volume elements and flow elements. These elements were then connected in an alternating manner (e.g. volume, flow, volume) to form the flow network. Volume elements determine the system's states by keeping track of the mass and energy flow into and out of the volumes. The volume elements use the resulting instantaneous mass and internal energy contained within the volume to determine all relevant system states required by the simulation (e.g. pressure, temperature, enthalpy, viscosity, speed of sound).

To increase model accuracy over the large range of temperatures within gas turbine, real gas, rather than ideal gas, properties were employed. Real gas properties were implemented by pre-generating lookup tables using NIST's REFPROP where internal energy and density (determined in the volume elements) were inputs into the lookup tables, and the remaining relevant states were outputs. Additionally, due to meaningful differences in gas properties between fresh air and exhaust, real gas properties were generated for each mixture.

Each volume element also contained an additional thermal mass (separate from the gas's internal energy) to capture the influence of the heat stored within the mechanical structure surrounding that volume. Each volume was then connected to the thermal mass by means of a heat transfer element. Further each volume's thermal mass was also connected by means of a heat transfer element to the ambient environment to capture external losses.

The combustor was treated as a volume element in which the mass flowrate of the fuel, along with its lower heating value (LHV), was added to the gas's energy as an external heat source. While detailed combustion modeling (chemical kineties, flame-out, etc.) was not needed for this HIL application, the model does switch from air to combustion gas properties within the combustor, and heat input was limited by stoichiometry in the event that excessive fuel was injected resulting in a rich mixture

Each volume element was connected to the next by means of flow elements which controlled the mass/energy flow into and out of each volume. A range of flow elements, including lines and orifices, were used in the model. Orifice elements, where flow was predominately a function of pressure differential, also included compressible gas effects such as including choked flow. More complex flow elements such as lines also included steady/transient frictional losses and fluid inertia.

The turbomachinery flow elements (compressors and turbines) were the only components predominantly empirical, rather than physics, based. This is because the physics behind turbomachinery operation are highly complex and a simplified physics-based representation which could run in real-time would likely prove insufficiently accurate for this application. Instead empirically derived maps (lookup tables) were used for each of these elements in which shaft speed and pressure ratio were inputs, and efficiency and mass flowrate were outputs. This information, along with the relevant turbomachinery equations, were then used to determine both the mass/energy flow into and out of the turbomachinery (which influence the volume elements), and the resulting shaft torque (which influence the rotational system). As such the turbomachinery flow elements also served as the connection between the gas flow and the mechanical (rotational) subsystems.

The AGT1500 contains additional elements such as inlet guide vanes (IGV) which influence flow into the LPC, and the power turbine stator (PTS) which influences the PT operation. The effect of these elements was captured within the LPC/PT turbomachinery elements by including IGV/PTS angle as an additional dimension within the empirical lookup tables. An abridged version of the model's causality for the LPC is shown in Figure 8.

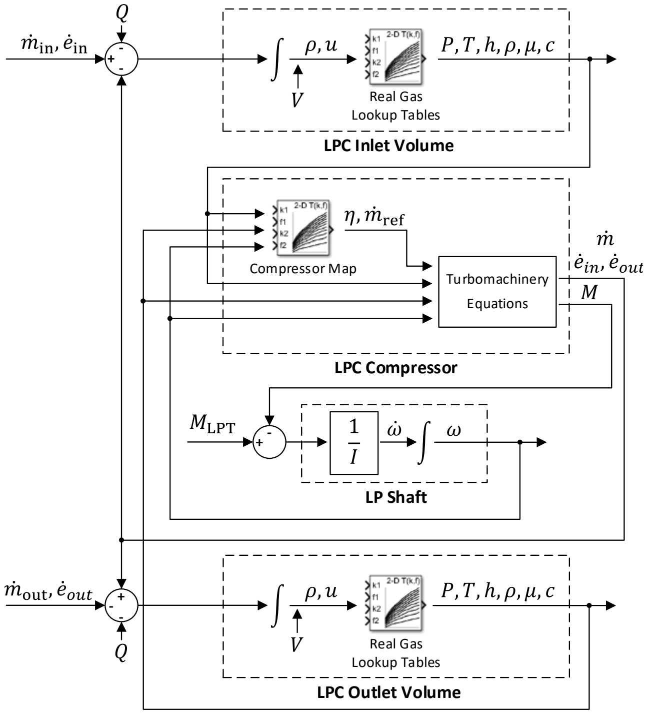

Figure 8: Model Causality

In addition to the internal states of the gas flow path, the model was configured to allow the ambient conditions to be modified as they can have a strong impact on system performance and dynamics. Ambient conditions which could be adjusted included altitude, temperature, and relative humidity.

Though much less complex than the gas flow path, the HIL model also includes three rotational state points: low/high pressure gas generators and the power turbine. These were modeled as simple reflected inertias with various torques applied from the turbomachinery, internal/external loads from various components including the starter motor, and frictional losses.

The overall HIL model was built using a *causal*, as opposed to *a-causal*, modeling approach where the model's arbitrary computational causality was explicitly defined. All of the Simulink code used within the plant models was custom developed by

Czero and provided to RTCS in an unlocked form to enable future modifications to the HIL plant models as needs and applications change.

Based on an evaluation of the neXtECU controller rate, the physics of interest contained within the AGT1500, the stability of the plant model, and the capabilities of the LABCAR hardware, a simulation rate of 1.3 ms (770 Hz) using a 4th order Runge-Kutta formulation was selected and achieved real-time operation on the HIL hardware. (Note neither the 4th order solver, nor the time step chosen, was selected based on capturing certain dynamics, rather they were chosen as a suitable balance between stability with computational efficiency). To achieve this simulation rate, the gas turbine model was optimized to reduce computational expense while enhancing stability and reliability. Examples of reducing computational burden include using fixed spacing on the lookup tables with pre-lookup functions and excluding physics such as wave dynamics.

Stability was enhanced at the given step size by slightly increasing the capacitance of certain small volume elements to reduce stiffness. Increase the size of these volumes was done methodically by comparing their dynamic performance with the correct volume sizes under smaller time steps while running off-line to ensure that these changes did not meaningfully influence the relevant system dynamics. Rate limiters were placed on certain elements to prevent unrealistically fast changes in flow resulting from the fixed time step solver. Additionally, limits such as anti-windup integrators were included in certain elements to ensure the integrators would not be swamped by a large instantaneous change in conditions which would have otherwise proved difficult for the system to recover from.

While the AGT1500 HIL model is predominantly physics based, there are invariably second order physical effects not included, and parameters, such as heat transfer coefficients not perfectly defined. As such a common practice when developing plant models, whenever possible, is to calibrate parts or all of the model using measurement data. This process serves two purposes. First it improves the model’s predictive accuracy across a spectrum of conditions. Second it provides the model a degree of validation which enhances the end user’s confidence in the model’s accuracy, as well as highlighting any potential issues within the plant model which require additional refinement from a model development perspective.

As this HIL model was intended to support controller development on an existing platform, RTCS had access to high-quality steady-state and transient data acquired in one of GVSC’s heavily instrumented dynamometer cells. This steady-state data was used calibrate the HIL model, while the transient data was used for validation purposes. While this data could have been used to calibrate any number of parameters, the most effective approach was to calibrate parameters which could have the largest overall impact on the system’s operation. In this case it was determined that the preferred approach was to correlate the HIL model to the dyno data by calibrating the mass flowrate, efficiency, and torque of the five turbomachinery components. This approach provided up to fifteen parameters which could be adjusted to increase model accuracy.

The calibration process began evaluating the system to match each calibration parameter with a single state point measured in the dyno which could be directly affected by it. For example, the measured and simulated inlet flowrates were matched by tuning the LPC’s mass flowrate predicted by the empirical lookup table.

For each operating condition undergoing calibration the process began by initializing the plant model in a stand-alone mode (i.e. not connected the HIL system). The control inputs measured in the dyno cell (fueling rate and IGV/PTS positions) were applied to the model and the high pressure, low pressure, and power turbine shaft speeds were fixed at their measured values (fixing the shaft speeds was done to lessen interactions between components within the model in order to make calibration a more feasible process as the desired shaft speeds were already known). Next the first calibration parameter (LPC mass flowrate) multiplier was tuned online using an integral controller with the objective of matching the measured and simulated inlet flowrates. Once the residual error fell below a certain tolerance threshold the next online integral controller was activated to tune the next parameter. This process continued until all the mass flowrate and efficiency multipliers were tuned.

Next the torque multipliers were calibrated in coupled pairs (e.g. the LPC torque multiplier would increase while the LPT torque multiplier would decrease by a reciprocal value) until the net torque on each shaft was zero. With this approach once the model was run freely under the same operating conditions, with the same calibration factors, the shaft speeds would equilibrate to the desired speed. This online calibration process was run until the residuals on every calibration point fell below the tolerance threshold, at which point the simulation was terminated and the resulting calibration factors recorded.

This calibration process was repeated using an automated routine for the full range of operating conditions with multiple discrete dyno runs to help prevent overfitting to one specific case. Rather than applying fixed calibration factors to the model, the model's accuracy was further improved by incorporating variable calibration factors tied to a specific system state. It was determined that the calibration parameters were strongly correlated to the referred high-pressure compressor shaft speed (NHR). As the model was calibrated using multiple dyno runs over a range of close, but not exact, operating conditions, the final calibration maps could not simply be an interpolation between these discrete points as that would result in severe overfitting. Instead a version of a zero phase lag variable weight moving average filter was employed to produce a smooth average of these inconsistently spaced discreet points.

Once complete, these fifteen calibration multipliers were implemented in the HIL model using lookup tables as a function of NHR. On average these calibration parameters were within +-5% of nominal (one) indicating the baseline model without calibration factors was already relatively accurate.

As a final step the plant model was validated against transient data not used in the calibration process. Similar to the calibration process, the validation process ran with the model operating in a stand-alone mode with fuel flowrate and IGV/PTS actuator positions measured on the dyno applied to the model. Now, however, the low and high speed gas generators were free to spin at the speed determined by the model's physics (the output shaft speed was still fixed to the measured value as a detailed dynamometer model was not included).

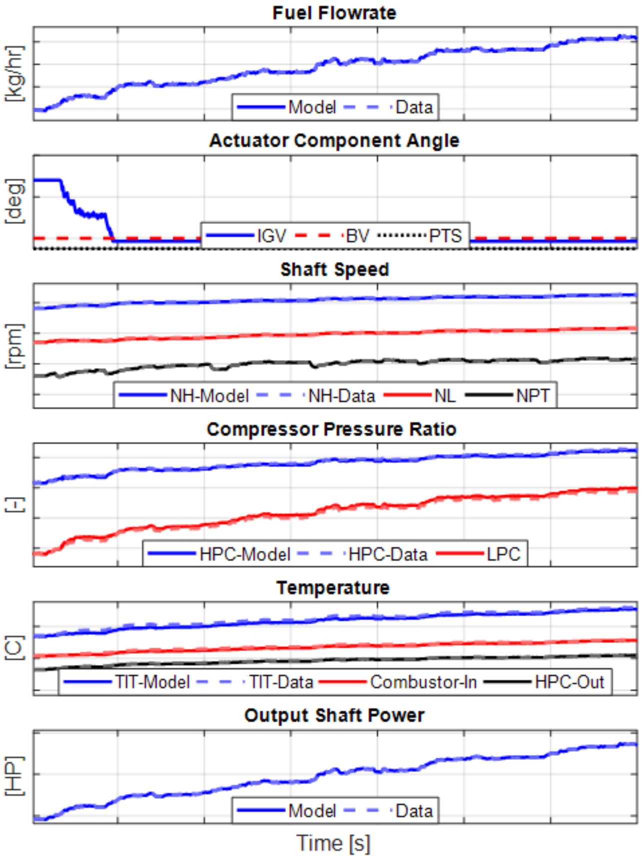

Figure 9: HIL Model vs Measured Dynamometer Data

Once the model was initialized and brought up to the operating conditions, it was held there for a period of time to enable all the internal components to reach to steady-state temperature (as thermal mass has a large impact on system dynamics). The model was then run through the transient data set and the resulting states recorded. One of these validation cases, a relatively steady increase in system power from a moderately low to a high power point is shown in Figure 9.

In this figure simulated states (HIL model) are shown as solid lines, while dashed lines of the same color indicate the respective states measured in the dyno. These results show a high degree of correlation between the plant model (operating using the same parameters/time step/solver as when running on the HIL system) and the dyno data. This provides confidence in the AGT1500 HIL model that, to a large degree, it accurately reflects the AGT1500 gas turbine and can be used as a surrogate in the initial controller development, tuning, and validation efforts.

X1100-3B1 Transmission and Abrams Vehicle Dynamics

The primary purpose of the Allison X1100-3B1 and Abrams vehicle dynamics plant models was to provide more accurate real-world response to the AGT1500's output shaft than would be achieved with a simple dynamometer model. As such a somewhat lower fidelity model was appropriate than would be required, for example, for detailed clutch control. Model complexity was reduced primarily by lumping components, such as individual gears within the transmission, together as well as neglecting higher frequency physics such as torsional dynamics. Nevertheless, the plant model was constructed in Simulink using a similar approach to the AGT1500.

Figure 10 shows a schematic of the transmission module. Staring from the input shaft on the top of the figure which is connected directly to the AGT1500's output shaft, power flows into the transmission (not shown are parasitic loads such various fans and an alternator connected to the input shaft and included in the plant model). Power from the transmission's output shaft then flows through a series of planetary gears and out to the tracks through the drive sprockets.

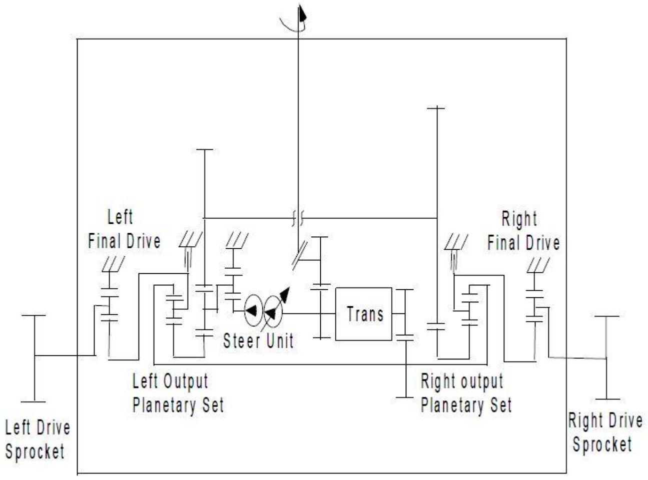

Figure 10: Allison X1100-3B1 Transmission Module [5]

One unique aspect of high-speed tracked tanks, compared to other vehicles, is their use of differential steering. Differential steering is accomplished by operating the left and right tracks at different speeds to turn the tank. The ability to drive the tracks at different speeds using a predominantly mechanical transmission is achieved in the transmission module using a cross-drive steering mechanism. This mechanism (as seen in Figure 10) consists of a separate planetary for each track with both planetary's ring gears connect to the transmission's output shaft, and the carrier gears connected to their respective track drive sprockets. Both planetary's sun gears are then connected though a drive and idler gear such that when one sun gear rotates one direction, the other gear rotates the opposite direction. Due to the planetary gearing kinematics rotating the sun gear in one direction causes the carrier (output) gear to speed up for a given input (ring gear) speed, while rotating it in the opposite direction causes the output speed to decrease.

This drive gear is driven by a small hydrostatic (continuously variable) transmission powered by the transmission's input shaft. When the hydrostatic transmission's motor is fixed to zero speed, both tracks rotate at the same speed and the tank moves in a straight line. By rotating the hydraulic motor at different speeds and directions the tracks operate at different speeds and the tank's motion is controlled.

The cross-drive steering mechanism was included in the HIL model as differential steering can present a very high torque demand at low speeds (even when accounting for the lateral torque transfer capabilities of cross-drive transmissions), an operation which was desirable to capture for the AGT1500 controller validation. Finally, an integrated controller for controlling the torque covert's lockup clutch, as well as gear shifting, based on shift maps was included in the HIL model.

While inclusion of the cross-drive steering mechanism was beneficial as it enabled an important high torque/ low speed operation to be captured by the HIL model, a traditional straight-line vehicle dynamics model was no longer sufficient as it would be incapable of accurately capturing loads during differential steering. As such a more complex tracked vehicle dynamics steering model was used (this inclusion also increases the overall utility of the Abrams's HIL model for other applications). The tracked vehicle dynamics model used was a modified form of a transient tracked vehicle steering model derived by Özdemir [6] (Figure 11) which is a variation of the well-established steady-state tracked vehicle steering model derived by Wong [7].

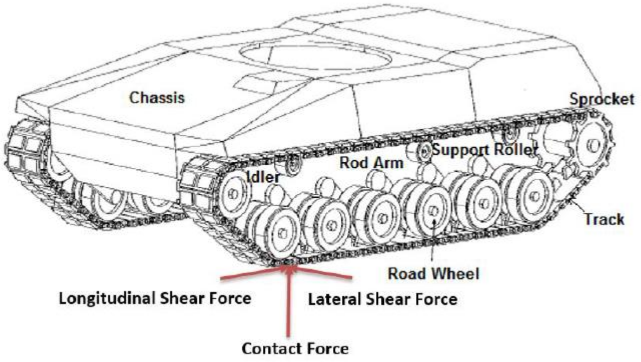

Figure 11: Tracked Vehicle Dynamics Model [6]

This vehicle dynamics model contained several features unique to tracked vehicles including modeling the contact patch beneath each of the Abram's fourteen road wheel which were further discretized into four sub-patches. The influence of sprocket angle and track pre-tension were included (which influences normal force distribution on the road wheels), as well as lateral/longitudinal static and dynamic weight distribution resulting from vehicle geometry and motion. This normal force distribution, along with velocities and slip angles calculated under every contact sub-patch, were used to determine individual shear forces between the track shoes and the ground. These shear forces, along with external loads such as aerodynamic drag, grading force, and additional rolling resistance, were used to determine the overall sprocket loads and vehicle motion.

Calibration/validation of the drivetrain and vehicle dynamics model was accomplished using a set of reference data for the M1A2 Abrams. To minimize error, validation of this portion of the plant model was performed independently from the AGT1500 plant model. Engine brake torque from the reference data set was applied to the transmission module's input shaft and ran through the drive cycle. The vehicle's baseline and simulated speed profiles for the validation case are shown in Figure 12.

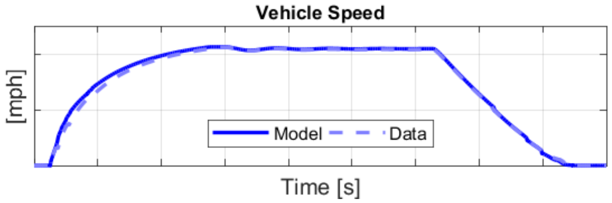

Figure 12: Drivetrain/ Vehicle Dynamics Validation

Using this approach helped to validate both the overall plant model, and the internal transmission controller. The plant model was validated as the only baseline data input into the system was torque from the AGT1500. For the baseline and plant model's velocity profile to match using this approach, all the parasitic loads and inertias must also match (validating these portions of the model).

Additionally, the lockup clutch and shift schedule controller were validated by ensuring these events occurred at roughly the same points in both data sets. From inspection it can be seen that there is relatively good correlation between the plant model and the baseline data. This provides confidence that the transmission and vehicle dynamics will provide relatively accurate loads and transient response to the AGT1500 HIL model.

4.3. HIL Hardware and Deployment

Thus far the individual plant models have been described. These individual plant models must be combined and configured for use on the HIL hardware and deployed to form the overall HIL setup. For the neXtECU evaluation the Abrams HIL model was deployed on one of RTCS's ETAS LABCAR HIL systems. RTCS's LABCAR system is a high performance configuration designed specifically for HIL applications and features a powerful multi-core processor for running the plant models, and a large assortment of I/O to emulate a variety of analog and digital signals being received from, and sent to, the neXtECU.

Internally the plant models track system states and flows using physical quantities (e.g. temperature, mass flowrate, displacement, speed, etc.) in base SI units. These parameters are generally incompatible with data transfer over the wiring harness and must be converter to/from values such as voltage, current, and frequency. Conversion of sensor/ actuator data between the electrical and physical quantity domains occurs in input and output translation layers connected to the base plant model (shown in green/blue respectively in Figure 13).

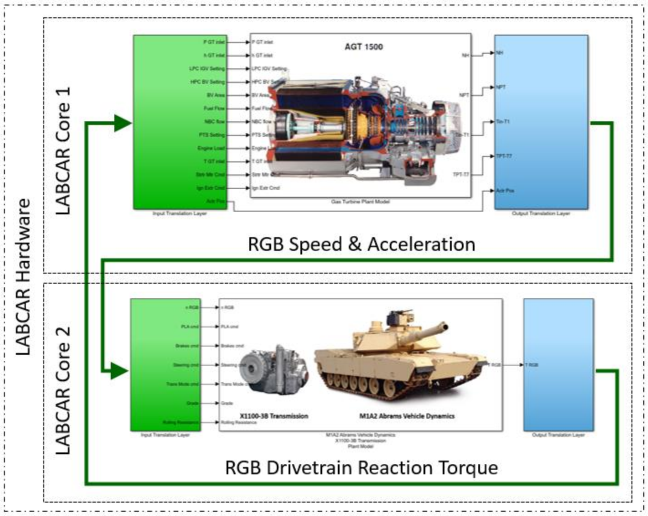

Figure 13: HIL Model Implementation

To enable the highest degree of fidelity and stability possible for the AGT1500 HIL model, the plant models were deployed on the LABCAR hardware in such a way as to maximum the computational resources available to the AGT1500. Computational resources were maximized by deploying the AGT1500 and drivetrain/ vehicle dynamics models on separate cores of the LABCAR processor. Interactions between the two systems occurs through the AGT1500's rear gearbox (RGB) output shaft. RGB shaft speed and acceleration calculated in the AGT1500 plant model is output and read in by the drivetrain/ vehicle dynamics model. Based on this speed and acceleration the drivetrain/ vehicle dynamics model determines the resulting RGB torque which is then fed back to the AGT1500 model. Both plant models were configured to run at the same 1.3 ms fixed time step to ensure data transfer consistency.

A final sub-system which has not yet been discussed is the HIL system's user interface (UI) which is realized though LABCAR's Experimental Environment. A schematic containing the various components and signal flows is shown in Figure 14.

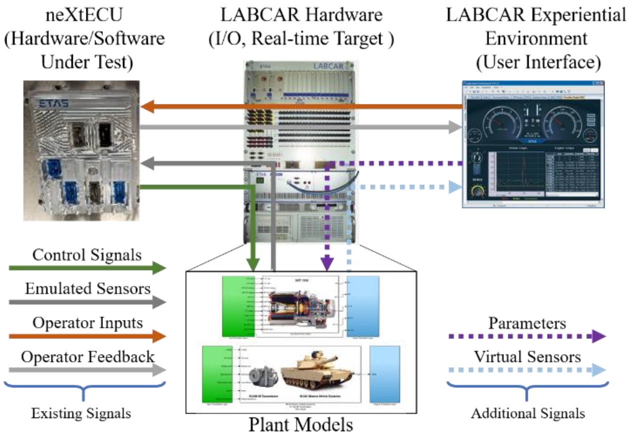

Figure 14: LABCAR HIL Setup

The UI performs several important roles. First it allows the emulation of user input devices such as key-on/ignition, throttle, gear select, and steering (though these could also be provided through a physical mock-up of a driver interface). These user input signals from the UI are either output over the LABCAR I/O to the controls hardware such as key-on and throttle, or sent to the respective plant model such as gear select and steering. A second function of the UI is to provide additional control over, and inputs to, the plant models. For example the user may input settings through the UI such as altitude and ambient temperature for the AGT1500 model, or grade and terrain (rolling resistance) for the vehicle dynamics model. Finally, the UI provides feedback to the user from both the controller and the plant models. This can include feedback such as the engine/vehicle speed normally output by the controller to an operator's dashboard, to intermediate state points from the HIL model which are not normally measured but may be highly valuable from a development and diagnostics standpoint.

5. SUMMARY

In this paper an overview and benefits of HIL/SIL methodology as they relate to the US Army's neXtECU common powertrain controller platform were discussed. This was followed by a reference example in which the M1A2 Abrams's AGT1500 gas turbine, drivetrain, and vehicle dynamics were modeled and deployed on RTCS's LABCAR HIL platform in support of exploring the neXtECU as a potential controller for the AGT1500. This work proved successful and demonstrated both the benefits of HIL methodology for military systems controller development, as well as the power and flexibility of the neXtECU to control a wide range of advanced systems.

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