ABSTRACT

Hardware-in-the-loop (HIL) simulation is a real-time testing process that has been proven indispensable for the modern vehicle dynamics, powertrain, chassis and body systems electronic controls development. The high quality standards and robustness of the control algorithms can only be met by means of detailed vehicle plant simulation models. In the last few years, several efforts have been made to develop detailed plant models. Several tools for the vehicle modeling are available in the market and each tool has different and distinct advantages. This paper addresses ways that dSPACE Automotive Simulation Models (ASM) can support the model-based development processes. Additional modern software tools that were used in connection with the ASM are LMS AMESim and Mathworks SimDriveline (of Simscape). ASM is an open Matlab/Simulink model environment used for offline PC based simulation and online real-time platform HIL testing. The combinations of system models from different suppliers typically require significant adaptation effort. dSPACE's ASM are ideally adapted to dSPACE hardware-in-the-loop simulators with real time capability whereas the AMESim environment requires a special procedure to make it compliant with dSPACE real-time hardware. This paper describes how AMESim vehicle dynamics, SimDriveline automatic transmission models and ASM parallel hybrid vehicle models are integrated for a dSPACE HIL real-time simulation environment.

INTRODUCTION

Today, depletion of petroleum resources with rising fuel prices have globally become a reason for concern, and it is commonly thought throughout the world that current automotive technology will need to be adapted or replaced for the future. To provide significant reductions in oil use and CO\textsubscript{2} emissions there are a variety of different technology options \cite{1}. The most promising is fuel economy improvement. Improving the fuel economy of vehicles has a crucial impact on the amount of oil imported. So far, the most promising technologies are hybrid electric vehicles (HEV). Hybrid vehicles, using current internal combustion engines (ICEs) as their primary power source, and batteries /electric motors as energy buffer, have much higher fuel efficiency than those powered by ICEs alone. A typical hybrid electric vehicle combines several complex components in its powertrain such as combustion engines, electric motors, battery, automatic and/or power split transmission, intermediate clutches, etc. HEV contains complex interaction between different powertrain devices and incorporates complex electronic control unit (ECU) network. For the vehicles of the future, comprehensive ECU tests are more necessary than ever before, as the complexity and extent of the software increases at a breathtaking speed \cite{2}. The V-cycle is a widely recognized approach in the development of electronic control units (ECUs) which incorporates offline controller development to HIL testing at the end of development cycle. Development of ECU's and to test its
Automotive Simulation Models (ASM) are modeled in MATLAB/Simulink. Simulink’s signal based modeling methods are very flexible. The mathematical modeling used in Simulink is its most important property. One advantage with the signal flow modeling used in Simulink is that it can be applied on many systems from different domains, as long as the equations describing the system behavior are known and they can be expressed by state space equations. However Simulink is difficult to use efficiently. It requires expertise in several areas like math, physics, and programming. Deriving system level equations is difficult and implementation of new models can be difficult to read and maintain. Moreover, it is necessary to know which inputs are available and which outputs must be calculated in order to connect it with the rest of the system. On the other hand, AMESim and SimDriveline uses a physical modeling environment where pre-defined components of different physical domains can be interconnected using a drag and drop style to create a complete system for modeling, simulation and analysis of mechanical, electrical, hydraulic and pneumatic components. Model reflects the structure of the system. System level equations are derived automatically. New technologies or designs can be easily incorporated into the model. With the physical modeling software, simple and complex systems can be modeled in one environment more easily than with Simulink’s signal-based methods. Physical system modeling is simpler to work with, but is less flexible than the dSPACE ASM modeling environment. Since ASM is developed with native Simulink blocks it can be adapted to a wide variety of powertrain systems and offers maximum flexibility. The premise of the paper is that components from various modeling environments could be combined to produce the best possible simulation for ECU testing. Paper shows an example of such an integration of dSPACE ASM models, with AMESim vehicle dynamics and Transmission from SimDriveline for parallel hybrid electric vehicle.

CONFIGURATION OF PARALLEL HEV

Parallel hybrid design blends the torque of an electric motor/generator along the IC engine torque. In this drivetrain IC engine supplies its power mechanically to the wheels as in a conventional IC engine powered vehicle. It is assisted by an electric motor that is mechanically coupled to the drive-line. Figure 1 shows the configuration of parallel HEV. In ECU network, hybrid control unit (HCU) manages powertrain, electric and chassis ECU’s such as engine ECU, transmission ECU, motor control unit (MCU), battery management system (BMS). ECU’s are connected by bus systems and each ECU interacts with its plant by means of sensors and actuators. ASM models show several powertrain components. Combustion engine and electric motor coupled to drivetrain and drivetrain is connected to vehicle dynamics.
an open and closed-loop driver is included as well. All parameters can be altered during run time.

Usability of the model strongly depends on parameter handling. Parameterization is an important aspect in modeling of automotive systems. dSPACE ModelDesk is a tool for parameterizing ASM models. It also provides project handling and allows parameter sets to be downloaded to offline and online simulations. MotionDesk has been developed as a complement to the dSPACE tool chain to visualize the movement of mechanical objects in the 3-D world.

dSPACE Simulator test runs can be visualized and automated from PC. The ControlDesk software is used during test development to create layouts and test sequences that are tailor-made for the application.

**ASM PARALLEL HYBRID ARCHITECTURE**

The Figure 2 shows the top level of a parallel hybrid vehicle ASM model. The MDL block contains the dynamic plant models - dSPACE ASM, Simulink & AMESim components. The IO block contains the dSPACE real time interface (RTI) blocks which are interfaces between plant models and the dSPACE hardware. These blocks can be used to build real time code, and to download and execute it on dSPACE hardware. In addition to the RTI blocks, the IO interface subsystem consists of blocks for scaling signals, providing test automation access, and switching between different configurations. MDLInterface block defines single point location from which the user can access the dynamic model. In this block signals can be converted into user-specific units without disturbing the SI unit-oriented signal flow in the real model. The parallel hybrid model is structured in several main components.

Figure 3 shows the first layer of parallel hybrid model with seven components SoftECU, Gasoline Engine, Battery, Motor, Drivetrain, Vehicle dynamics and Environment. The engine, motor, drivetrain, and the vehicle dynamic blocks are connected via shaft speeds and shaft torques. The gasoline engine model can be used in combination with real controllers in a hardware-in-the-loop environment (online mode), or for simulation of a gasoline engine in combination with software controller algorithms (offline mode). The two yellow blocks to the left and right of the model blocks manage the signal mapping from and to the I/O. They also manage the signal flow to and from the soft ECU for offline simulation.

**ENGINE**

Model used for engine is gasoline engine basic model. This model is a Simulink model used to simulate spark ignition combustion engine. The engine model simulates a fuel system, an engine combustion system, an air path, an engine coolant system, and an exhaust system. The engine model contains components for an air path with a throttle and a manifold, and a piston engine which includes the air intake and combustion simulation. The air path simulates the intake manifold dynamics and the throttle. The air flow is controlled with the throttle. A fully opened throttle allows the engine to receive all of its required air mass flow, which results in the maximum engine torque. The intake manifold model calculates the manifold temperature, the manifold pressure, and the mass inside the manifold. The fuel system injects the fuel for the combustion into the manifold. The fuel system calculates the fuel mass flow by the measured injection time. Cooling system model calculates the cooling water temperature from the actual torque and the friction torque. Engine combustion system describes the air flow through the inlet valve and the torque generation by the combustion. For gasoline basic engine actual torque is calculated by a table based on the engine speed and the relative air mass flow.
Figure 3. Parallel Hybrid Main Components

BATTERY
The battery model calculates the terminal voltage, the battery state of charge (SOC) and the battery temperature as a function of the charge and discharge current. The terminal voltage model takes into account several battery effects such as voltage of each battery cell according to SOC, inner resistance, inductance, diffusion behavior of battery. The parameter values for the different resistances, the inductance and capacitances are parameterized for one battery cell. The heat generation and dissipation takes account of effects like heat from the main reaction, loss reaction, ohmic losses and heat flux due to thermal radiation. The SOC is calculated from battery current, temperature and loss current.

ELECTRIC MACHINE
Electric machine is modeled as a permanent magnet synchronous machine (PMSM). General modeling approach which is well known from industrial drive motor is used for HIL simulation purpose [4]. As the rotor has no electrical circuit, only the stator windings are modeled. The PMSM is modeled using \( dq \) notation in the synchronously rotating reference frame. The real-time capability with respect to calculation time and real time I/O is considered during modeling.

Figure 4. Simulink2Simdriveline Block

As shown in Figure 5, similar Simulink2Simdriveline block is created for motor shaft. Actuator inputs and sensor outputs are Simulink signals that are used to interface with rest of the ASM model components. As shown in figure rotational
inertias are specified for different bodies such as engine, motor. Motion sensor blocks gives engine speed and motor speed as an output.

Figure 6 shows converter with lockup clutch block which incorporates torque converter from SimDriveline library.

![Figure 6. Converter with Lock-up Clutch](image)

Figure 7 shows seven-speed Lepelletier transmission model from SimDriveline transmission templates, and how it is incorporated in the overall vehicle model. Transmission model is based on planetary gear and ravigneaux gear. Properly engaging a transmission in a particular gear setting requires engaging a certain number of clutches. Transmission controller block consisting of Simulink Lookup and Transfer Fcn blocks, converts the single clutch control signal to a set of six clutch signals that shifts the seven speed transmission through a fixed gear sequence. Single clutch control signal for transmission controller comes from the ASM SoftECU for transmission. ASM Soft ECU for transmission controls the seven speed Lepelletier transmission. It engages the gears and controls the lockup clutch according to lever position. In the drive position, the SoftECU engages the first gear and shifts automatically according to the transmission output speed and the accelerator pedal position. The lockup clutch is also controlled according to vehicle speed and to the accelerator pedal position. Driveline model is connected to SimDriveline environment which defines solver for the system. One of the requirements is that the gear ratios should always be positive. If a gear ratio vanishes or becomes negative, the SimDriveline simulation stops with an error. In SimScape there are some special ports that are connected with special connection lines. These connection lines are not normal Simulink lines. As a result, variables are not available in RTI’s variable description file for these ports and connection lines.

**VEHICLE DYNAMICS**

In this example AMESim vehicle dynamics model is used. LMS AMESim is simulation software for the modeling and analysis of one-dimensional (1D) multi-domain systems using physical modeling environment [6]. As shown in Figure 8 vehicle dynamics model is created in AMESim. Figure shows AMESim to Simulink interface. The AMESim to Simulink interface enables you to construct a model of a subsystem in AMESim and to convert it to a Simulink S-Function.

As shown in Figure 9 the S-Function can then be imported and used into ASM model. The AMESim RT (Real-time) option enables the export of an AMESim model to a real-time environment for use in hardware-in-the-loop (HIL) simulation.

AMESim environment requires a special procedure to make it compliant with dSPACE real-time hardware. After the system (in this case longitudinal vehicle dynamics) has been modeled in AMESim, an interface s-function has to be created to receive and/or send signals to Simulink model. The s-function is generated by switching to parameter mode and import it to ASM/Simulink model while keeping the AMESim model open for Matlab to have access to the s-
function and trace files which would otherwise be lost if the AMESim model is closed. Standard AMESim-Simulink interface uses Simulink solver so no need to worry about the solver for real-time interface. However, S-function parameters of 1 and 0.01 have to be used to have AMESim results printed with an interval of 0.01 sec. Since AMESim does not know the name of the ASM system that the code will be used in, TRC file AMESIMMODELNAME_.trc is generated. To take this into account in dSPACE, the file must be renamed to ASMMODELNAME_usr.trc. The build command also needs to have access to the name of the AMESim system in the circuit. This information is supplied by the extra argument AMESIMMODEL=VehicleDynamics on the make command. Depending on the Matlab version and real-time dSPACE software used, AMESim has a specifically design template make file (TMF located under $AME/lib) for building the application.

The main advantage of the AMESim is to create high precision models without writing a single line of code using mathematical representation of the system behavior. However, its limitation lays with the difficulty of altering the equation of the system. Because the equation is built within the physical element, adding or removing functionality is difficult and thus is less flexible than ASM models.

ENVIRONMENT

The environment subsystem is used to define driving maneuvers for the vehicle by means of stimulus maneuvers or at a specific vehicle speed controlled by the driver model. The road subsystem allows you to set environmental conditions like road grade, friction coefficient, environmental pressure, and temperature.

SOFT ECU

The soft ECU block contains models for Engine controller (ECM), transmission controller (TCU), hybrid controller (HCU). For the motor control unit real ECU has been used. ECM calculates injection time based on intended lambda.
value, optimum ignition angle and throttle position. TCU controls the automatic gearbox. HCU soft ECU controls engine on/off, torque request co-ordination, battery management. Torque request co-ordination includes torque request for IC engine that has to be operated by soft ECU gasoline and torque request for electric motor that will be operated by real ECU.

REAL TIME SIMULATION - SOLVERS USED AND LIMITATIONS

For the real time simulations fixed-step solver with balancing accuracy and simulation speed must be used. For the current system ASM plant model is using fixed step solver with ODE1 method and time step of 1 millisecond. Electric component models for ASM have to be solved with an appropriate solver. The equations are solved numerically by discrete methods, i.e. the Simulink solver has no effect on the equation solving technique. Three main solvers that were utilized in the implementation are Forward-Euler, Backward-Euler and Tustin.

Efficient testing of ECUs for electric machines requires fast measurement and analysis of several closely associated signals. In this example, electric machine model runs at a faster rate than the rest of the model. Electric machine model is computed at the carrier frequency of the PWM gate drive signals from the ECU. The PWM signals coming from ECU are measured by the DS5202 PWM measurement solution, while calculated motor current signals are sent back to controller by means of analog voltage signals (DS2202 DACs). Electric machine subsystem is driven by hardware interrupt block of DS5202. Since separate tasks can interrupt each other, the transfer of data vectors between them can also be interrupted, producing inconsistent data. Simulink's rate transition blocks are used to handle the task transition.

SimDriveline models use the Simulink solver suite, so solver settings are same as the general Simulink models (ASM). Fixed step solver with larger tolerance and step size results in less simulation accuracy. It is always good to obtain reference results with variable step solver then find right balance between accuracy and simulation speed using fixed step solver. Sample times of all SimDriveline blocks are always continuous so these blocks cannot be used with discrete solvers. For the fixed step solver clutch velocity tolerance value must be specified either in each clutch or in the connected Driveline Environment block. In real time simulation most SimDriveline parameters are not tunable; this is one of the limitations of SimDriveline. It is not possible to generate a code from SimDriveline model that contains one or more S-functions generated from other SimDriveline models.

Some AMESim systems are difficult or impossible to solve using Simulink solver. In this case user can use co-simulation (in Simulink), or import the Simulink model into AMESim and use the AMESim solver for everything. In current system main purpose is to test and develop controller in ASM environment. For this purpose AMESim-Simulink interface uses Simulink fixed step solver. After the AMESim S-function is imported into Simulink, it is verified that the AMESim/Simulink system can run and give correct results using a fixed step integration method with a time step of 1 millisecond. By adding AMESim parameters to the AMESim watch facility it is possible to change AMESim parameters while the simulation is running. The limitation is that many AMESim parameters are not used directly in the calculation, but they are preprocessed in the initialization phase of the simulation. The number of AMESim S-function blocks allowed in the Simulink model which is compiled with RTW is limited to one. It is possible to group the different AMESim systems together in AMESim and import the AMESim system as one S-function.

CONFIGURATION OF A HIL SIMULATOR FOR A PARALLEL HEV MODEL

Figure 10 shows interface level between ECU and HIL model. For HIL simulation, motor control model is transferred to MicroAutoBox which will act as a real ECU and entire plant model is transferred to dSPACE simulator.
Electric motor needs more complex control system [7]. Electric drive controller has different requirements regarding the HIL simulator. Control loop of electric drive is not only closed by motor speed but also by a current loop. In combustion engine HIL simulators, only low power actuators are controlled electrically, while in electric drive entire controlled power is electrical. In order to test under real power conditions, complete motor test bench has to be integrated. However with signal level simulation, it is possible to test real time motor controller without real inverter.

In signal level simulation real voltages and currents are not present physically, but only in simulation. This type of HIL testing is advantageous because of low cost, no safety issues. From hardware point of view there is no limitation about machine parameters. We can test 2 kW or 40 kW electric motor with the same test setup. Each physical effect can be taken into account Offline- and Online- Simulation with the same model. Disadvantages of signal level simulation includes separate power stages necessary and there is no test of real power stages.

In this example simulation model is connected to standard I/Os of the motor controller, such as interfaces to motor position sensor, communication interface CAN. Electric motor in simulation model uses current control loops computed every PWM period from ECU. An accurate measurement of three phase center pulse PWM control signal is performed by a hardware ds5202 board.

**MODEL DESK**

For parameterizing and managing the parameter sets of parallel hybrid, dSPACE ModelDesk is used. Figure 11 shows overview of ModelDesk. Arrows indicate that ModelDesk can be used for offline Simulink simulation of ASM model and online real time simulation on dSPACE hardware. Parameter files are created and assigned to each model component, for example, differential, tires and road. Complete vehicle parameter sets are created and managed. ModelDesk has additional capabilities such as Road generator which is GUI for defining road segments and creating test tracks. Maneuver editor is used to create driving maneuvers such as follow road, increase acceleration, brake, driver aggressiveness, etc. Traffic editor can create traffic scenarios for displaying simulated traffic situations such as vehicles overtaking and changing lanes. The Plot Manager can be used to visualize signals of the simulation model and to manage the simulation results. The new blocks for AMESim vehicle dynamics and SimDriveline are stored in custom library. These custom libraries are integrated in ModelDesk. The ModelDesk automation interface allows to change parameter values, select roads, and specify maneuvers using scripts.
TURNAROUND TIME
The turnaround time for a task is the time that passes between the triggering and the end of its execution. For real time simulation an overrun situation occurs if a task is requested to start but has not finished its previous execution yet. To avoid overrun situation, solvers and time step setting should be such that it provides accurate results while permitting real-time simulation. Table 1, shows the turnaround time on HIL simulator for different model combinations. Based on the comparison it is seen that there is 30 μs difference between ASM model and combined model. However based on complexity of model components from different environment turnaround time will vary. Parallel hybrid model is running in multiple timer task modes. Figure 12 shows turnaround time for HIL simulator, MicroAutoBox and PWM hardware interrupt which is 262 μs, 24 μs and 11 μs respectively.

CONTROLDESK USER INTERFACE
The entire graphical user interface is implemented with dSPACE ControlDesk. It provides all the functions to control, monitor and automate experiments and makes the development of controllers more effective. User can easily interact with system and manage the real-time experiments using ControlDesk GUI as shown in Figure 13 below.

Figure 14 shows motor controller input and output signals. The output of the ECU is low PWM pulses that will operate the inverter. Three phase duty cycle as shown in figure is fed to DS5202 FPGA based PWM capture solution. The outputs of motor model are current and speed signals and fed back to the ECU.
Figure 12. Turnaround Time for Different Tasks

Figure 13. ControlDesk Graphical User Interface

Figure 14. Measured Duty Cycle and Three Phase Current on ECU
CONCLUSION

From the controller point of view a HEV is a complex interaction of powertrain components and controller functions. For the development of such controller functions dSPACE offers all necessary components: Automotive Simulation Models (ASM) for plant modeling and proper I/O interfaces and real-time systems. Real time simulation of a system requires balance between complexity of model, solver type, solver settings and real time hardware. ASM provides several capabilities that make it easier to use it for real-time simulation. ASM can be used throughout the development process as controller development on PC and Hardware-in-the-loop (HIL) test of real controller. With the use of ASM ready to use plant models, developer can focus more on control systems development. ASM also allows integration of models developed in different environment. AMESim and SimDriveline model has been integrated in ASM and tested on real time system. Solver settings and limitations for each tool are described. In addition to this ModelDesk allows handling of complex parameter set and managing of simulation run and simulation result.

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