Using a Rapid Prototyping Environment for Developing a Propulsion Control Unit for a Hybrid Vehicle
## Contents

1. Synopsis ..............................................3
2. The Vehicle ..........................................4
3. The Vehicle System Architecture ........5
4. Function Development with ASCET ..........6
   4.1 Accelerator Pedal Logic ......................6
   4.2 Calculation of the Maximum Torque .....7
   4.3 Torque Distribution .........................7
   4.4 Torque Rise Limits .........................8
   4.5 Function Modeling .........................8
5. Testing ...............................................9
   5.1 Offline Simulation .........................9
   5.2 Rapid Prototyping .........................9
6. Advanced Propulsion Functions ..........10
7. Conclusion ........................................10
8. List of Abbreviations .......................11
1 Synopsis

Automotive hybrid propulsion systems are the subject of much discussion these days. Virtually all automakers and a majority of Tier One suppliers are working on related concepts and components. With a view to providing his students with a practical, hands-on educational encounter with these highly topical subject areas, mechanical engineering professor Dr. Prexler came up with the idea to develop, with the full involvement of his students, a roadworthy prototype with hybrid propulsion within three semesters. At the Landshut University of Applied Sciences, a joint project of the Faculties of Mechanical Engineering, Electrical Engineering, and Computer Science has developed a road-ready, serial plug-in hybrid named “MBL ex-drive” within a mere 18 months (see Figure 1).

Figure 1:
Serial plug-in hybrid based on a BMW X5.
2 The Vehicle

The basic vehicle was a BMW X5 supplied by BMW AG. After removing the entire stock powertrain, propulsion is now provided by two electric motors integrated in the axles (Figure 2), retaining the four-wheel drive capability of the original vehicle. The X5’s third row of seats made way for the lithium-ion battery array with its total output of 400 V (Figure 3). As the term plug-in hybrid implies, the batteries are conveniently charged from a standard 230 V mains outlet. In the X5 hybrid, the braking energy, which would be lost in the case of a conventional drive system, is recovered through recuperation and returned to the batteries. As a result, battery capacity provides a range up to 100 kilometers, or 63 miles.

A significant increase of the vehicle’s operational reach is accomplished by means of a so-called range extender. It consists of a diesel engine powered generator, which recharges the batteries while driving. Due to its original use in an emergency generator set, the stationary diesel engine operates with optimum fuel efficiency. This type of hybrid is known as a serial hybrid. Compared with a parallel hybrid, which combines two kinds of propulsion systems, it is of decidedly lower complexity.

Figure 2: Components of the hybrid propulsion system.

Figure 3: Array of lithium-ion batteries in rear of vehicle.
The powertrain of the stock X5 was not the only thing to be modified; changes to the vehicle system architecture were also required. In order to keep required interventions with the existing vehicle network as minor as possible, a new CAN bus, the Hybrid CAN, was added to handle the new hybrid functions. This new bus accommodates the connections with the inverters (DMC) that supply alternating current to the two electric drive motors (Figure 4).

Although the original engine management module (DME) remains in the vehicle, it now handles only the acquisition of the accelerator pedal position. The ECU used for the new hybrid functions is an ES910 Rapid Prototyping Module, which does double duty as a gateway between the original powertrain CAN and the Hybrid CAN. The ES910 also handles the bus communications of the spatially distant transmission control unit. In conjunction with a compact module for which installation space was found in the passenger foot well, this arrangement makes it possible to execute all functions in real time.

Figure 4:
CAN bus architecture.
Function Development with ASCET

The development of the new hybrid functions made use of the proven development tools from ETAS. The objective was to develop, within the shortest possible time, a prototype that would facilitate the gathering of hard data.

Function development relied on the ASCET development tool. The propulsion function was structured by the system architecture (Figure 5). The top level represents the human machine interface (HMI) and the calculation of the maximum torque. Below there is the torque distribution and the torque rise limitation. The lowest level is responsible for the CAN communication.

4.1 Accelerator Pedal Logic

Because the conventional brake was not modified due to safety concerns, the accelerator pedal provides both acceleration and electric braking (recuperation) functions. Accordingly, and depending on the recuperative status, accelerator pedal travel was divided into three individual functional ranges (Figures 6 and 7):

- **Braking range**
  Braking decelerates the vehicle in the direction opposite to the selected driving position.

- **Inactive range**
  In this range, the vehicle is neither accelerated nor decelerated.

- **Acceleration range**
  The vehicle accelerates in the direction corresponding to the selected driving position.
The recuperation function must also provide an option for deactivation. In this way, overcharging the batteries during long downhill travel is prevented. As regards the accelerator pedal characteristic, a distinction must therefore be made whether recuperation is active or disabled. Depending on this status, the position of the accelerator pedal, and the selected driving position, the corresponding nominal torque value is calculated. The application of a given function range and the calculation of the applicable nominal torque value is based on the following principle:

- **Braking through recuperation**
  With an accelerator pedal position between 0 and LIMIT_R_T, and if the recuperation function is also enabled. Here, an accelerator pedal position of 0% corresponds to full recuperation (maximum nominal reverse thrust), LIMIT_R_T [%] of the accelerator pedal position corresponds to a nominal reverse thrust value of 0%.

- **Inactive range**
  In this range, a nominal torque value of 0 Nm is always generated and sent to the DMCs:
  - From 0 through (LIMIT_R_T + ∆) of accelerator pedal position, when recuperation is not permitted and/or disabled.
  - From LIMIT_R_T through (LIMIT_R_T + ∆) of the position with active recuperation.

- **Acceleration range**
  Propulsion in the direction determined by the selected driving position (LIMIT_R_T + ∆ to 100%). The accelerator pedal position LIMIT_R_T + ∆ corresponds to a nominal torque value of 0 % of the maximum possible driving thrust, and 100 % accelerator pedal position to 100 % of the maximum possible driving thrust, respectively.

The recuperation function may be activated only once the accelerator pedal is positioned in either inactive or acceleration range. This means that initially the division shown in Figure 6 is to be maintained. Only if and when the prerequisites have been met, shall the division as per Figure 7 take effect. This is done to exclude the possibility of a sudden brake power loss during the braking procedure. In the event that the recuperation function were to again become available after a while, the division shown in Figure 6 shall be maintained until the accelerator pedal is again positioned in the range between LIMIT_R_T and LIMIT_R_T + ∆ or in the acceleration range. Only then shall the division according to Figure 7 be applicable. This is intended to prevent a sudden brake application that the driver may not expect. The driver is informed by a signal whether the recuperation function is enabled or disabled.

### 4.2 Calculation of the Maximum Torque

The temperature of the water-cooled inverters and motors as well as the batteries are monitored. To prevent component overheating, the maximum torque value for both axles are determined on the basis of the temperatures. Here suitable characteristics are used separately for each axle. An additional influencing factor is the charge state of the batteries. Overcharging or exhaustive discharge of the battery is prevented by the limitation of the torque.

### 4.3 Torque Distribution

Once the nominal torque has been determined, the same must be distributed to the two axles. Accomplished in a variable fashion, this distribution is based on the following strategy:

1. Initially the torque is distributed to the two axles as a function of vehicle road speed. This is done with the use of a characteristic containing several axis points, plus linear interpolation.

2. As a next step, the nominal torque values for front and rear axle are compared with the calculated limit values. The strategy is to build up the overall torque demanded by the driver as quickly as possible. If a torque value on a given axle exceeds the limit value, the torque on that axle will be limited. However, in complying with the driver’s intentions, every effort is made to achieve compensation by raising – within the bounds of limit values – the torque on the other axle as much as possible. This means that the ideal torque distribution to both axles is abandoned in favor of the torque demanded by the driver.
4.4 Torque Rise Limits

Electric motors are capable of producing very high torque almost instantly. To prevent damage to the drive train, the value of the torque change acting upon the drive shafts (1st derivation of torque as a function of time) is limited to $\text{MAX\_TRQ\_CH} \ [\text{Nm/s}]$. This is accomplished by building up the torque to be generated by the electric motors by means of a ramping function. Because an instant drop of the torque to a lower value with the same sign, and/or to 0 Nm, cannot cause any damage and is therefore possible (Figure 8).

4.5 Function Modeling

All propulsion functions were developed with the ASCET tool, with the deployment of block diagrams, state machines, and conditional tables.
5 Testing

5.1 Offline Simulation

In a first step, offline simulation was used to test the behavior of the software components. Figure 9 shows an example of such an experiment, used to test the torque rise limitation. The timeline of the input variable and output variable are shown as green and red curves, respectively, where the input variable is stimulated by a sine-wave function. It is apparent from the graph that the torque at the output builds up only with a certain rise. At the point where the green and red curves intersect, the value of both curves (and thus the input and output variable) is reduced. Once the zero point has been bisected, the torque at the output slowly increases in the other direction, maintaining the specified rise. In this way, it is possible to confirm the correct behavior of the class.

5.2 Rapid Prototyping

In the next step, the INTECRIO tool facilitated the transfer of the function model to the ES910 Rapid Prototyping Module. Prior to testing the module in a real-world vehicle, another quality control step verified the overall functionality vis-à-vis a residual bus simulation.

With the objective of optimizing vehicle drivability by means of tweaking a number of multifaceted parameter sets, the new propulsion system is currently being tested on both dynamometer and actual road trials. In this effort, the focus is on torque distribution to the vehicle’s two axles, in consideration of the energy available, the temperature of all components, and the vehicle’s speed. Experimentation also includes the manipulation of a variety of accelerator pedal characteristics. Initial tests have provided evidence that – given the appropriate calibration – drivers become used to the combined drive and brake pedal rather quickly.

At this time, testing is still performed directly through the facilities of the INTECRIO tool (Figure 11), with mechanical engineering and computer science students working hand in hand with each other. As a next step, an INCA user interface that will enable mechanical engineers to calibrate the driving functions without assistance is under development.
Based on the current basic functions, several students are in the process of developing advanced propulsion features. Going beyond comfort functions such as cruise control or stopping on a hill, these new developments also address safety aspects, e.g., traction control for the electric propulsion system. These functions, too, are specified with the aid of ASCET, with the objective to develop individual encapsulated software components in the manner of AUTOSAR. As is the case with the entire project, the intent to provide the students with hands-on training according to contemporary educational approaches takes front and center.

For the upcoming semesters, plans for using the same vehicle as a development and training platform are in place. The range of topics will cover quad-motor propulsion, high-voltage fuses, battery management systems, and instrumentation and driver control concepts.

Figure 12:
Monitoring the internal operating states with INTECRIO.
With the X5 Hybrid project, the Landshut University of Applied Sciences has demonstrated that it is possible to build preproduction hybrid vehicles without the need to forego the familiar comfort of a conventional vehicle. The development of the new hybrid functions relied on the ETAS tools ASCET, INTECRIO, INCA, and ES910, which were deployed in accordance with the classic Lifecycle Process Model (V-Model). The confluence of these tools and the power of rapid prototyping technology enabled the specification, verification, and ultimately the execution of the functions onboard the vehicle. In this way, the computer science students were able to breathe life into the vehicle built by the engineering students in a relatively short period of time.

For detailed, German-language project information, visit www.ex-drive.de.

The article is published by:

### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>CAS</td>
<td>Car Access System</td>
</tr>
<tr>
<td>DMC</td>
<td>Digital Motion Control</td>
</tr>
<tr>
<td>DME</td>
<td>Digital Motor Electric</td>
</tr>
<tr>
<td>EHB</td>
<td>Electrohydraulic Brake</td>
</tr>
<tr>
<td>GWS</td>
<td>Gear Selector Switch</td>
</tr>
</tbody>
</table>

**CAN**
Data bus commonly used in both vehicles and automated technology.

**CAS**
Vehicle access control. Inter alia, the function determines the status of Terminal 15 (“Ignition ON”).

**DMC**
Supplies alternating current to electric drive motors.

**DME**
Conventional engine management module of stock BMW X5.

**EHB**
BMW X5 brake system with brake booster, Antilock Braking System (ABS), and Electronic Stability Program (ESP).

**GWS**
Selector of the automatic transmission.
Did you know,

- a passenger car powered by a conventional internal combustion engine actually delivers 7 percent of the fuel energy consumed to the point “where the rubber meets the road”.¹

- a fully charged battery weighing 275 lbs. will provide a range of 100 miles, but 275 lbs. of diesel fuel provides a range of just under 940 miles.²

- the annual lithium carbonate production of 90,000 metric tons is sufficient to equip 12 million hybrid vehicles.³

---

¹ Source: Technical University Munich / HdT-Conference “Electric/Electronic in Electric and Hybrid Vehicles”, March 2010
² Source: EVONIC 2009 / ADAC Technologies for the Future, Munich 2009
³ Source: http://www.lithiumaktien.com/EN/566/1590