EFFECTIVE MODELING AND SIMULATION OF INTERNAL COMBUSTION ENGINE CONTROL SYSTEMS

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EXTENDED SUMMARY

1. Problem Statement

Nowadays, control engineers are faced with the task of simulating complex dynamic systems. The complexity of the simulated systems usually arises from the desire to model as closely as possible the dynamic system and from the very nature of certain continuous-time and discrete-time systems that have a changing dynamical behavior depending on the occurrences of so-called discrete events. For example, the internal combustion engine of an automobile is characterized by the crankshaft angle which determines one of four cycles; namely intake, compression, combustion and exhaust. In this case, the sudden change from one cycle to another can be considered as a discrete event. In the literature, these systems are sometimes referred to as event-based or hybrid dynamic systems [1].

Internal combustion engine control systems are difficult to model, especially within a real-time setting. Fixed time step simulations of the engine control systems are required for a subsequent hardware-in-the-loop (HIL) simulation of the simulated engine dynamics in closed-loop with the actual electronic control unit; however, the events associated with the crankshaft angle can take place in between the fixed time steps. This causes a discrepancy between the actual crankshaft event occurrence and the discrete-time detection of the crankshaft event by the simulated system, when one uses conventional numerical simulation techniques such as n-point Runge-Kutta methods [2] or Forward/Backward Euler methods or the Trapezoidal technique [3]. The latter techniques are routinely used in the fields of digital control [4], [5] and filtering [6] whereas the former methods are well known in the area of digital simulations [7]. Consequently, using the conventional time-based techniques, there are unavoidable differences between the simulated and the actual engine dynamics [8].

In more details, one can easily understand the types of problems involved with fixed-step simulations of internal combustion engine systems by considering, for instance, the process of integrating a continuous signal with reset of the integrator done at time instants other than integral multiples of the fixed step size. This kind of integration takes place, for instance, on the fuel and air flow rates at the inlet of each cylinder. In this case, there
will be errors between the output of the simulated integrator and that of the theoretical integration. This is so simply because the simulated integrator can be reset at integral multiples of the fixed step size, and not at the time instants at which the theoretical integrator is reset, with the conventional numerical integration techniques. However, keeping in mind that the simulations should approximate as closely as possible the behavior of the actual integrator, the discrepancy between simulated and actual integrators creates a problem of accuracy of simulation. One approach to solve the problem of accuracy is to use time steps of variable sizes, as available with such commercial software as Simulink™ [9]. Briefly, a simulation using variable step sizes is based on an algorithm that selects a step size according to signal tolerances, disregarding time-related constraints. This sort of scheme has the disadvantage of possibly resulting in time consuming simulations, thus preventing rapid prototyping and, even worst, considerably slowing down the execution of a batch of simulations, which can be performed, for example, for engine power, torque and fuel consumption optimization studies over its operating range [10]. Furthermore, if one is interested in assuring compatibility of the simulations with hard real-time constraints, the variable step size solution has to be discarded; that is, with an eventual connection to input/output boards and to a timer card for HIL simulations, a fixed step size must be selected. Another approach to the time-based simulation of internal combustion engine systems is to utilize a relatively short step size (fixed time step size). Yet, in the case of highly complex event-based systems, it is possible that infinitesimally small step sizes be necessary to achieve successful simulations, and that the control law development be slowed down considerably.

2. Proposed Solution

This paper proposes a novel modeling and simulation method as well as an integrated software/hardware solution to effectively model, from a time-domain point of view, and simulate internal combustion engine control systems, including the execution of batch of simulations. By an effective technique, it is understood that: (1) the signals of interest obtained with the simulations are relatively close to those of the actual internal combustion engine control system; (2) the execution of the simulations is time-bounded in that it either achieves real-time or is relatively fast, depending on the desired goal; and (3) the model can be executed as part of a HIL framework with the proper boards installed.

In order to solve the problems inherent to the conventional fixed-step simulations of internal combustion engine control systems, a new Simulink™ library of blocks has been created. This library comprises a set of discrete-time blocks that use a compensated discrete-time simulation algorithm. The key idea behind the new blocks is that of including an algorithm that compensates for events taking place in between simulation steps. For instance, in the case of an integrator with reset, the discrete-time integrator of the new library does not reset its output to zero, as is the case with the conventional techniques, but rather it fixes its output to a value very close to that of the actual integrator, at the discrete time step; a value that is obtained with the compensatory algorithm. This provides a relatively accurate simulation of the internal combustion
engine control system with respect to the theoretical system when the blocks of the new library are correctly placed in the engine model.

In more details, the new library comprises a comparator block, a discrete-time integrator, a latch and several relational operators. The comparator block generates a trigger signal whose value depends on the result of a comparison between the two inputs to the block. The discrete-time integrator block uses numerical methods to approximate the integration of its input signal and comprises an algorithm that compensates for the occurrence of discrete events in between sampling instants. The key feature of the latch block is that it incorporates a method that compensates for the triggering taking place between sampling instants. Finally, the relational operators perform standard operations on signals while compensating for transitions occurring between the sampling times.

The major features of the new Simulink™ library are summarized as follows:

- It compensates for the errors introduced by events occurring in between the simulation steps;
- It allows fast simulations of internal combustion engine control systems;
- It is suitable for hard real-time applications;
- It is easily adaptable for distributed real-time simulations on an integrated software/hardware system comprising QNX-based target nodes communicating via a Firewire link and a Windows-NT-based host station (which includes Simulink™ and RTW).

3. Simulations

The schematics of the nonlinear, event-based internal combustion engine control system are shown in Figure 1. The engine model, or plant model, contains the representations of the principal components of the engine; that is, intake (manifold) and engine dynamics, as well as torque generation (mean torque, torque modulation for each cylinder), with the blocks of the new Simulink™ library rightly placed.

The simulations were carried out with the following objectives in mind: achieving (1) fast and (2) real-time simulations with relatively high accuracy with respect to the theoretical model.

First, for fast simulations, the closed-loop model was distributed over three Windows-NT-based, 550 MHz, 128 MB RAM Pentium III microprocessors connected via the high-speed cLAN communication link. The distribution of the model in executables running on individual processors was facilitated by the use of the RT-Lab™ software [11]. It should be pointed out that the splitting of the model on a set of microprocessors was done in such a way as to achieve a relatively equivalent computational load on each machine. The measured signals were the engine speed, and the mean and the instantaneous torques. In short, the simulation scenarios carried out on the internal combustion engine model, which incorporates the new blocks, were relatively accurate since the scaled L₂ and L₁ error norms were less than one tenth those obtained with the conventional fixed-step
techniques. Furthermore, the simulations were significantly accelerated as compared to variable-step simulations carried out with Simulink™.

![Diagram of internal combustion engine control system]

Second, for real-time simulations, the internal combustion engine control system shown in figure 1 was distributed over two QNX-based, 233 MHz, 64 MB RAM Pentium II microprocessors connected via the Firewire communication link. Once again, the RT-Lab™ software was used for the distribution of the executables. It was found that the real-time simulations were yielding relatively accurate results for step sizes of 500 microseconds, whereas this was not the case with the conventional fixed-step simulation techniques at step sizes of 500 microseconds and lower, since the conventional methods do not provide any compensation of the events taking place in between the sampling instants.

4. Conclusions

It was shown that the use of the blocks of a new Simulink™ library, named RT-EVENTS, to model an internal combustion engine control system results in simulations that are relatively accurate, and that execute in real-time or that are relatively fast with respect to the variable-step simulations. Moreover, the simulations of the internal combustion engine control system were executed within a software/hardware integration framework that allows any simulated component, whether it be the controller, the plant, the actuator or the sensor, to be removed and replaced by its actual counterpart. This is ideal for subsequent HIL simulations.

References


