Real-Time Estimation based on Multibody Dynamics for Automotive Embedded Heterogeneous Computing

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Abstract

For the last decades, the automotive industry has been improving the ride & handling and the safety of vehicles. Electronic Control Units (ECUs) have extensively contributed to these improvements [1]. Most of these ECUs need information from multiple sensors placed in the vehicle for getting all the information required to execute their control actions. However, in some cases, this information is not available or implies the use of expensive sensors. As an alternative, a state observer based on a model of the vehicle (or part of it) and a reduced number of sensors can be used to create virtual sensors [2, 3, 4] for the missing information required by the ECU. A difficulty linked to this solution is the execution of the state observer and the model of the vehicle in *real-time* on the ECU. Several studies have developed models of some parts of the vehicle or a simplified model of it with state observers for control applications [5-6]. In [2] the multibody model of a complete vehicle with a state observer is executed with good accuracy, but the computational complexity of the simulation was too high to be able to simulate it in *real-time*. Finally, in [7], an indirect state observer is presented and the simulation of a multibody model and its state observer reached *real-time* in an *on-board* CPU. This strategy is promising but the computing hardware used in this research does not correspond to the computational power available in ECUs of commercial vehicles. These Electronic Control Units often have low computational capabilities. However, new heterogeneous processors, embedding *ARM* cores and Field Programmable Gate Array (FPGA), are being used to develop the next generation ECUs. FPGAs are devices than can be fully reprogrammed to fit any application with high performance. ECUs in the automotive industry are mainly used in the execution of control algorithms. The implementation requirements of all the control systems that a vehicle includes, would need a high number of ECUs, which increase the complexity of the network system. For reducing the number of ECUs, powerful heterogeneous processors are chosen to execute these algorithms [8]. Nevertheless, at the date of writing, no approach exists for the use of heterogeneous FPGAs with multibody models.

The aim of this work is to satisfy the requirement of *real-time* implementing an *errorEKF* state observer [7] with a complete multibody model of a vehicle in an embedded heterogeneous processor. For this purpose, the multibody model of a car has been designed for embedded applications using tools previously developed by the authors [9]. The target hardware chosen for this work is the Zynq 7000 AP SoC of *Xilinx*. This System-On-Chip includes an *ARM* processor *Cortex-A9*, with two cores and an FPGA. In order to program the FPGA co-processor, the source code for the numerical computations has to be in the *VHDL* language. The source code has first been written in C/C++ and the translated into *VHDL* using the *Vivado* tool from *Xilinx*.

Different ways can be followed to test the computational efficiency of the implementation of the system (multibody model and observer) in the FPGA. First, the resources consumed in the FPGA must be taken into account: the more parallel the code is, the smaller execution time will be reachable, and the more area of the FPGA will be used. This requires, in case of complex models, to use a bigger FPGA at the expense of additional costs. Another option that is explored in this work is the use of different multibody formulations, which could result in a more efficient implementation. It is necessary to study different options regarding the computing time and consumed resources: execution of the entire multibody model in the FPGA and the state observer in the core of the ARM processor, implementation of some parts of the multibody model in the FPGA or execution of some matrix operations in the FPGA.

Preliminary results have been obtained in the simulation of a simple multibody model of a *quarter-car* following these different strategies. The *quarter-car* model was defined in natural coordinates [10], using the penalty formulation and with the trapezoidal-rule as integrator combined with the Newton-Raphson method. A 10 s maneuver has been executed with a time step of 4 ms at the heterogeneous processor.

Regarding to the different possibilities of combining the *ARM* processor with the FPGA, the first option explored was to execute the full model in the FPGA, and it was seen that the available resources of the FPGA were not enough, leading to the partitioning of the model. Two alternative options where compared: implementation of matrix multiplications in the FPGA co-processor or the matrix inversion on FPGA co-

processor. The results are shown in table 1.

Table 1. Time of execution of the quarter-car model

Configuration	All model in *ARM* processor	Matrix Multiplication in FPGA	Matrix Inversion in FPGA
Clock Cycles	1,55E+08	6,28E+08	1,44E+07
Time (s)	0.23	0.94	0.02

As can be seen, simulating the model with the matrix multiplications in the FPGA, leads to an excessive execution time. This could be due to the simplicity of the model, which results in small matrices and, therefore, the multiplication in the FPGA is not a significant computing time improvement, so the communication time makes the multiplication slower. However, the performance of the matrix inversion in the FPGA is substantially better than in the ARM processor, hence the communication times are far less relevant. It can be concluded that when complex models are used, the implementation of both matrix operations should lead to a more efficient and faster simulation.

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