Real Time Models of Automotive Mechatronics Systems: Verifications on "Toy Models"

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Abstract. Modern electric vehicles are complex mechatronics systems whose behaviour is highly influenced by the concurrent action of mechanical and electrical systems interfaced with complex control logics aiming to improve several aspect concerning energy management, vehicle stability, comfort and guidance. As a partner of the European Project Obelics (Optimization of scalaBle rEaltime modeLs and functIonal testing for e-drive ConceptS), authors have focused their attention in system integration and model optimization of electric powertrains with a particular attention to the problem of brake blending respect to different applications (smart energy management, vehicle stability, hardware in the loop testing of connected mechatronics systems). In this work authors introduce main features and possible usages of brake models that they have to develop within the Obelics Project. Proposed models have to be implemented and verified also for real-time implementation with a particular attention to RT-Implementation and Co-Simulation with models provided by other partners of the project. For this reason, authors introduce specifications concerning Real Time implementation not only in terms of scheduling of different tasks but also proposing a reference architecture of Real Time controller (An hybrid multi-core systems with on board FPGA) that should be used for the preliminary prototyping and testing of the proposed models. Finally, a preliminary "toy", simplified model is proposed in order to verify the feasibility of the proposed architecture respect to a future complete implementation and integration with the product of the research of the other partners of the project.

Keywords: Mechatronics · Real-time simulation · Multi-scale models
Multi-physics models · Brake blending

1 Introduction: Brake Blending, State of the Art and Involved Research Activities

Authors are members of a research team of Università degli Studi di Firenze, that are partner of the Obelics [1] (Optimization of scalaBle rEaltime modeLs and functIonal testing for e-drive ConceptS). In order to positively contribute to the project authors are focusing their attention on the problem of brake blending for road electric vehicles. Brake blending is a classic topic in railway engineering [2, 3] where electric and conventional braking are applied simultaneously in order to obtain an optimization of

G. Carbone and A. Gasparetto (Eds.): IFToMM ITALY 2018, MMS 68, pp. 141–148, 2019.
https://doi.org/10.1007/978-3-030-03320-0_15

maintenance costs (reduction of wear and loads to which are subjected friction components of conventional brakes) and an improvement of energetic efficiency allowing a regenerative transfer of the braking energy through the overhead lines to available loads represented by other trains or by static infrastructures, such as reversible power stations or energy storage systems [4]. If external loads for regenerative braking are not available, railway vehicles are also equipped with internal resistors to perform on board dissipative electric braking.

The term blending is used to indicate the control criteria of both conventional and electric braking that is implemented in order to assure desired performances avoiding any undesired dynamical effect that should arise from contemporaneous application of braking forces produced by different systems [5].

On road vehicles, optimization of electric blending is further complicated by the fact that exerted braking efforts also influence lateral stability. Also modulation of braking forces is used by on board control subsystems such as ESP(Electronic Stability Program) [6] or other torque vectoring systems to stabilize the trajectory of the vehicle. Energy recovered with regenerative braking has to be stored on vehicle accumulators which should not be able to manage required power transfer [7, 8], as example if the state of charge is too high or involved currents should be higher respect to known safety limits of the storage. In all these conditions even if the electric powertrain is completely efficient, regenerative braking efforts cannot be applied, so this potential unavailability has to be managed by the brake blending controller in order to produce a reliable behavior of the system. Finally, it should be noticed that the dynamical response of electric motors/actuation systems are much faster and more controllable respect to conventional internal combustion engines. As a consequence, electric traction should be used to perform a fast and precise multi-quadrant control of exerted torques contributing to modulate longitudinal efforts on wheels contributing to an enhanced behavior of on board subsystem such as ABS(Antiblockiersystem)-ASR (Acceleration Slip Regulation // Anti-Slip Regulation) [9], ESP etc. In literature [10–12] there is a wide variety of studies concerning this topic. Another interesting topic for research and design optimization is represented by powertrains with multiple traction motors or direct drive inwheel solutions. These unconventional solutions are very promising both for off-road or urban mobility applications as visible in the scheme of Fig. 1 where different examples taken from literature [12–15] are introduced.

Investigation and Simulation of Brake blending should be very interesting also for the development of high frequency inverters and energy storage management systems. In particular, high levels of reliability of energy storage systems involve a constant monitoring of high frequency interactions with traction motors and drive systems [16]. For this reason, it should be interesting to verify the behavior of the system when complex control tasks are performed by traction motors (as example high frequency modulation of exerted torques for torque vectoring). Frequency content associated fast control transients should be exploited to perform diagnostic identification procedures aiming to verify the current state of health of energy storage systems through on line spectroscopic identification procedures [17].

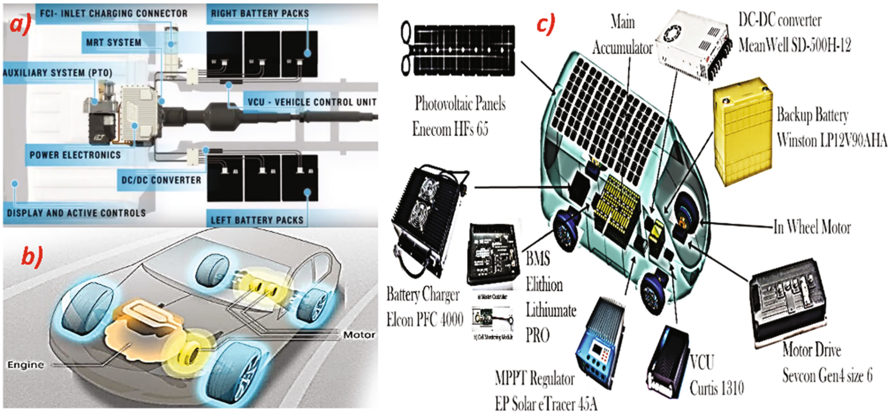

Fig. 1. Examples of multiple electric motors and electric powertrains, *(a)* conv. Gearbox with motors connected by MRT™(Multiple Rotor Transmission) [12, 13], *(b)* Torque Vectoring with multiple electric motors by Honda [14], *(c)* Four in-wheel vehicle [15]

2 Proposed Task Partitioning and Hardware Implementation for a Modular Real-Time Simulation

As explained in the introduction, advanced simulation of brake blending involves the evaluation of multi-scale and multi-physics phenomena that are described in Table 1. In particular, for the design of a modular simulation platform some preliminary evaluations from Table 1 should be useful: integration frequencies that should be needed to reproduce high frequency response of power electronic systems should be too high for real time implementation on a RTOS (Real Time Operating System) not only in terms of computational load but also in terms of jitter of the system. Management of I/O signals from external measurement or actuation devices (as example for Hardware in the Loop or Software in the Loop applications) should be simpler with FPGA(Field Programmable Gate Array). Modular structure and a discrete partitioning [18] between different tasks running on different threads should be quite mandatory, considering variety and number of subsystems that have to be implemented.

Many commercial products (as example from Matworks™ or from National Instruments™) allow some automatic or smart distribution of concurrent tasks between different cores. However, a good organization of tasks is fundamental to optimize computational efficiency. Authors adopted a physical based distinction between “Continuous” and “Discrete” subsystems. Continuous models represent physical systems whose mutual interaction has to be modelled minimizing delays introduced by the execution on a real time target which is necessary discrete.

Computational delays (due to task execution and data exchange between different tasks) are tolerable only if they are relatively negligible respect to the typical time scale of the phenomena that they have to reproduce as shown in Table 1.

Clearly, it should be easier the implementation on different threads of slow processes such as thermal and wear models since delays introduced by data exchange with

Table 1. Simulated Dynamical Behavior and corresponding integration features

System description	Physical domain	Continuous/Discrete (Num.Stiffness)	Mean integration freq. (ODE1 solver)
Multibody Vehicle Model	Mechanical	Continuous[a](Stiff)	10^3–10^4 [Hz]
Tire/Road Contact Models	Mechanical	Continuous[a](Stiff)	10^3–10^4 [Hz]
Hydraulic Plant/Brake Models	Mainly Fluid	Continuous[a](Stiff)	10^3–10^4 [Hz]
On board Digital Control Systems	Math/Digital	Discrete (Not stiff)	Typ. 10^1–10^3 [Hz]
Electric Motor and Drives	Electric	Continuous (Stiff)	10^5–10^9 [Hz]
Low Lev. Control of Power Devices	Math/Digital	Discrete (not Stiff)	10^4 [Hz]
Battery Models	Electro-Chem.	Continuous[a](Stiff)	10^3–10^6 [Hz][b]
Efficiency, Thermal and Wear Models (friction and power components)	Thermal/Other	Continuous[a](Not Stiff)	10^1–10^2 [Hz]

[a]All physical Systems are "Continuous" while discrete systems are typically represented by digital control systems to which is typically associated an execution sampling rate. When performing simulation with fixed step integrators, execution frequency of digital systems should be at least a magnitude order slower respect to the corresponding integration frequency of coupled continuous systems in order to avoid the risk of unrealistic coupling effects between systems that are modelled with the same discrete sampling rate.
[b]For batteries integration sampling frequency is strongly influenced by the kind of adopted model and its potential usage to investigate (or not) high frequency interactions with coupled electrical systems.

faster simulated physical phenomena should produce relatively small consequences on accuracy of results. On the other hand, models have to reproduce control algorithms and other processes that are discrete also in the real world. In this case the correct implementation of delays associated to data acquisition, communication and production of outputs are mandatory to correctly reproduce the dynamical behavior of simulated digital system. A correct implementation of discrete system is also useful to perform task partitioning since delays that have to be reproduced to fit a real physical behavior should be used to manage communication and data exchange between different threads on the real time platform. According to above described specifications authors have selected a possible hardware, described in Table 2, that should be used for real-time implementation of brake-blending models: proposed platform is substantially a hybrid multi-core real-time controller with a Xilinx FPGA. In this way simulation of most demanding tasks (such as the electrical ones of Table 1) should be implemented on FPGA. Remaining tasks should be distributed by the multiple cores of the controller according the following criteria:

- optimization of the flow of data that have to be exchanged between threads on different cores.
- optimal distribution of computational loads between cores.

Table 2. Specification of the RT Platform chosen for the preliminary real-time implementation and simulation of Brake Blending Models

Supplier/chosen board	Main controller//slave-communication	Slave-FPGA	Available I/O(For Exp. Activities)
dSpace/MicrolabBox* *RT Target for Matlab-Simulink™, Siemens Amesim™	Freescale QorlQ P5020, dual-core, 2 GHz // QorlQ P1011 800 MHz, 2 Int. Ethernet interfaces (host +I/O), USB 2.0 (“flight recorder”) and booting	Xilinx® Kintex®-7 XC7K325T FPGA	ADC: 8 14-bit //24 16-bit channels DAC: 16 16-bit channels DIO: 6 × Encoder// 2 × Hall sensor input// 2 × EnDat interface// 2 × SSI interface// Sync. multi-channel PWM Block com.PWM//2 CAN//2 x UART (RS232/422/485)// 1 × LVDS

These criteria are summarized in the scheme of Fig. 2: preliminary proposed configuration is relatively robust respect to delays introduced by data exchange between threads since it’s optimized respect to the coupled dynamics of simulated systems.

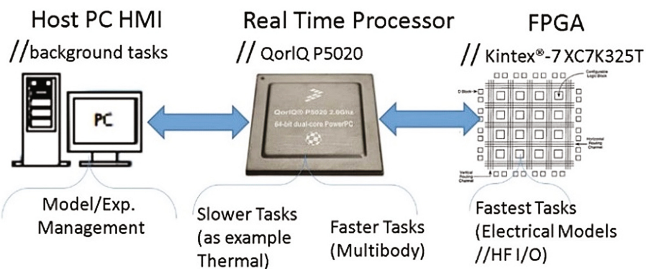

Fig. 2. Chosen Hybrid Controller (Freescale-multi core-Power PC controller and FPGA) with corresponding task partitioning

3 Preliminary Implementation of a Simplified “Toy” Model: Some Results and Observations

According over-introduced specifications, authors have assembled a simplified “toy” model of a vehicle with its main sub-systems. Aim of this activity is to verify feasibility and functionality of the proposed approach while more complex simulation modules (developed by other partners of the project) are still not available, since the activities are still in a preliminary phase. In particular authors, according project deliverables [19], are responsible for brake models. In order to properly simulate brake plant models also other interacting dynamical systems has to be simulated using Matlab Simulink™. For these activities, authors have preliminary considered the usage of simplified vehicle models (quarter vehicle and/or planar 7DOF one) in which the tyre-road interaction is modelled using a Pacejka model [20]. Electric Power train is currently simulated in terms of simplified transfer functions.. Also a simplified model of the energy storage system is introduced [21]. All the implemented models are integrated separately simulating different sampling frequencies and communication delays. In order to properly verify the portability of the code within different partners of the project each subsystem is compiled as a discrete Matlab-Simulink S-function™. This verification of code portability [22] is useful also for the conversion models also the FMI (Functional Mock-up Interface) format. FMI is an open universal co-simulation standard [23] to which have to converge all the models proposed in Obelics in order to assure a complete interoperability of the research products among partners.

In Fig. 3a and b there are some results referred to the simulation of a braking maneuver (simplified quarter vehicle model). Considered data approximately correspond to the loads applied to the motorized frontal wheels of city-car like with a total mass of about 1400 kg. In particular, it’s interesting the capability of the model of implementing some typical features of the brake blending: as visible in Fig. 3b applied electric torque is limited considering torque and power limitations of the drive system, including the unavailability of regenerative braking for very low speed.

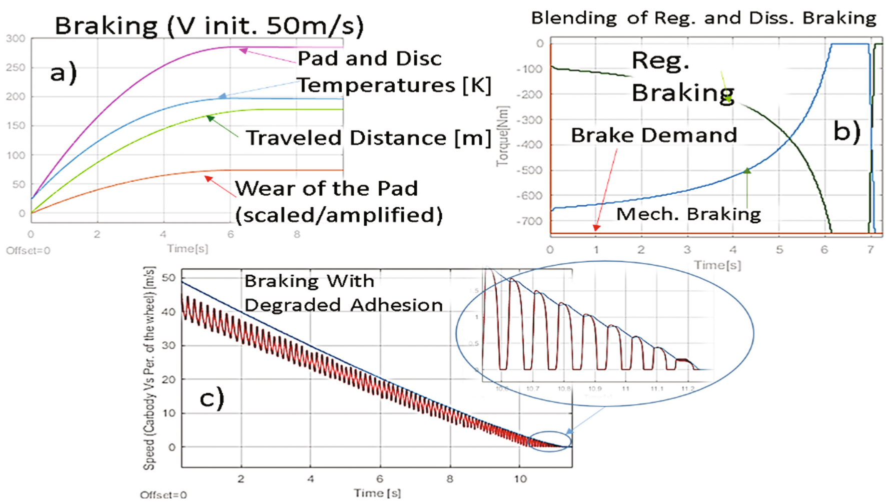

Fig. 3. example of preliminary simulation results, (a) results of braking simulations, (b) blending between mechanical and Electrical Blending, (c) braking with degraded adhesion

In Fig. 3c same simulation is repeated considering degraded road adhesion conditions. These results are quite interesting to verify model stability and reliability respect to delays and errors introduced by fixed step integrators (discrete or ODE 1 integration) and relatively large integrations steps (fastest tasks run at 10 kHz but most of the model is successfully working with 100–1000 Hz sampling frequencies). In particular, it's clearly noticeable the absence of "chatter" phenomena that are typically caused by delays introduced by discrete task partitioning in real time systems.

4 Conclusions and Future Developments

In this work authors have introduced preliminary design activities concerning real time simulation and optimization of brake blending models produced by University of Florence. Most innovative and significant results of these activities mainly concerns implementation procedures aiming to assure portability of produced code within different partners and simulation environments. As further development author wish to be able to further customize and develop the model respect to Use Cases proposed by Industrial Partners of the Project (Example of advanced prototypes of Electric Vehicles that should be simulated using the proposed tools). Also in order to assure the prescribed portability of proposed models authors will verify also FMI implementation and compatibility with advanced models proposed by the other partner of the project.

Acknowledgments. This work is part of the OBELICS project which has received funding from the European Unions Horizon 2020 research and innovation programme under grant agreement No. 769506.

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