Collaborative Engineering of Integrated Chassis Control for Ground Vehicle

Case study of lifelong learning technologies in automotive mechatronics

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Abstract—The paper introduces an approach to development and testing of integrated active chassis systems for the ground vehicle through intersectoral and interdisciplinary collaboration. The approach is illustrated by example of design of integrated control for the decoupled brake system, the active tyre pressure management and the active suspension elements. The corresponding demonstrator of sport utility vehicle is introduced. Testing procedures for the demonstrator are presented including remotely connected experiments at different locations. The paper explains how the development and testing processes are realized by way of knowledge transfer and experience sharing between academic and industrial collaborators.

Keywords—*automotive control systems; collaborative engineering; mechatronic education; integrated active chassis control.*

I. INTRODUCTION

Development of complex automotive mechatronic systems, starting from early design stages until experimental testing of full-scale prototypes and beyond, requires solving various research and technical tasks by highly skilled professionals with interdisciplinary background. Therefore, the interdisciplinarity should be one of key teaching elements integrated already in undergraduate and postgraduate education. The corresponding approaches have been developed in particular in many automotive mechatronics engineering courses covering four main subjects: mechanical, electric/electronic, control engineering and computer science [1, 2]. Furthermore, relevant university courses are traditionally using project-based methods to bring additional practical skills to the students [3, 4].

However, traditional educational schemes may not correspond to actual demands of industry. For example, in accordance with the Frost & Sullivan survey [5], several challenges can be expected to 2020 regarding educational policy and automotive industry:

- It is forecasted that the global growth rate of demand (+18.0%) of mechanical engineering graduates will be less the global growth rate of mechanical engineering graduate supply (+31,94%);
- At the same time, the skill sets and quality of the graduates may be not sufficient for OEMs;
- New paradigms in automotive industry, such as automated driving, connected vehicles and electric mobility, require extension of traditional skills of mechanical engineering graduates with strong interdisciplinary content (first of all, Information Technologies) allowing them a better understanding of the new market requirements

In this case of particular importance becomes acquisition of strong interdisciplinary and product-relevant knowledge through lifelong learning technologies. For instance, it can be efficiently realized with the collaboration of professional teams from different organizations and sectors. Taking into account the character of modern industrial processes for such complex products as automotive mechatronic systems, lack of wide intersectoral networking with an international dimension can be considered as a tangible barrier for rapid development and market implementation.

The content of lifelong learning technologies depends strongly on the target technological area, and various training and educational mechanisms can be adopted for these purposes. The presented work has a goal to introduce one particular case that is being realized by the development of the integrated chassis control with different mechatronic systems. The corresponding collaborative project uses specific training schemes for early-stage and experienced researchers and staff within the framework of Marie Skłodowska-Curie Actions (MSCA) established by the European Commission [6]. The proposed training format is realized through the Research and Innovation Staff Exchanges (RISE) scheme to support short-

term mobility of professionals at all career levels. Next sections of the paper will introduce interdisciplinary and intersectoral content of related training and development activities as well as the target configuration of the vehicle and its mechatronic subsystems. Particular attention will be given to the test platforms and cooperative testing procedures.

II. INTERDISCIPLINARY TRAINING TASKS BY EXAMPLE OF INTEGRATED CHASSIS CONTROL

Design of modern ground vehicles is characterized by increased number of mechatronic chassis and powertrain components. These on-board components can be interconnected through numerous informational and energy channels that leads to the effect of multi-actuation and emerging new concepts like integrated chassis control (ICC). Application areas of ICC relate not only to the traditional transportation sector of passenger cars and commercial vehicles but also to wide spectrum of off-road mobility, e.g. sport utility vehicles (SUV).

Formulation of efficient design and testing strategies for such technical object require deep understanding of many components, Fig. 1: (i) Tyre models for on-road and off-road conditions, terrain models as well as vehicle dynamics models to be implemented in the chassis controllers; (ii) Control engineering methods, e.g. adaptive control and control allocation, which are used in active chassis system controllers; (iii) The hardware components of ICC subsystems designed on a mechatronic base; (iv) Methods of real-time X-in-the-loop (XiL) and full-scale testing for ICC subsystems and the corresponding vehicle demonstrator.

Taking into account the presented interdisciplinary content, the training of professional developers of ICC can be reasonably organized in the form of project-based activities. In particular, these activities can include regular staff exchanges of involved researchers/engineers and lead to the development of joint vehicle demonstrator with new active chassis systems. Such approach is realized in the project EVE funded under the MSCA RISE scheme [7]. This project is being considered as the case study in the presented paper. The research and training project components are introduced in next sections.

Fig. 1. Interdisciplinary content of ICC design

III. OBJECTIVES OF COLLABORATIVE ENGINEERING

The global research and innovation goal of the discussed case study is to create a demonstrator of the sport utility vehicle equipped with several active chassis systems – the decoupled brake system, the dynamic tyre pressure control, the vertical dynamics control system - and their integrated controller. This demonstrator is considered as an open platform for validation, verification and feasibility studies related to (i) tyre and vehicle models; (ii) controllers of vehicle dynamics and mechatronic vehicle subsystems; (iii) state estimation technique; (iv) XiL testing technologies.

Within the framework of the EVE project, the global goal is advanced with a number of educational objectives:

- Knowledge transfer and experience sharing between participants from academic and non-academic sectors to create innovative products in the field of ground vehicle engineering based on the know-how of partners in mechatronics, automotive control systems, vehicle dynamics and experimental techniques;
- Professional development of the consortium members through intersectoral and international collaboration and secondments to unique research environments exploring knowledge and technologies in ground vehicle and mechatronic systems engineering.

Both the project goal and educational objectives allowed identifying required competences and a reasonable composition of the consortium that will be introduced next.

IV. KNOWLEDGE SHARING THROUGH CONSORTIAL TRAINING

The project-based training requires a balanced presence of participants from academic and non-academic sectors. With this in mind the presented project consortium includes various organizations with competences introduced in Table I.

TABLE I. PROJECT CONSORTIUM

Participant	Main Competence
<i>Industrial sector</i>	
Tenneco Automotive Europe BVBA (Belgium)	Active chassis systems, vehicle testing
dSPACE GmbH (Germany)	Hardware- and X-in-the-loop technologies
SKF (Netherlands/Sweden)	Load sensing bearings for force-based control applications
ESTEIQ Engineering Ltd (South Africa)	Multi-body dynamics software
Gerotek Test Facilities (South Africa)	Vehicle testing on proving ground in on-road and off-road conditions
<i>Academic sector</i>	
Technische Universität Ilmenau (Germany)	Brake system design, chassis design, vehicle system testing
University of Pretoria (South Africa)	Vehicle dynamics, vehicle testing
Virginia Tech (USA)	Tyre modelling, terramechanics
Instituto Tecnológico de Aragón – Itainnova (Spain)	State estimation methods
Chalmers Tekniska Högskola AB (Sweden)	Vehicle testing technologies on tracks and driving simulators
Technische Universiteit Delft (Netherlands)	Control engineering, human-vehicle interaction

Fig. 2. Examples of knowledge sharing channels by training. Legend: 1 – hardware- and X-in-the-loop testing; 2 – ride comfort; 3 – active chassis design; 4 – state estimation; 5 – multi-body system modelling; 6 – proving ground testing; 7 – tyre modelling and testing; 8 – advanced sensors for chassis control.

The mechanisms of intersectoral training, proposed in the EVE consortium, develop skills of participants by way of targeted knowledge transfer. In particular, researchers from academic organizations are gaining experience in (i) implementation of hardware-in-the-loop (HIL) testing technologies for different industrial applications, (ii) development of commercial software applications, (iii) practical skills of real-world testing of different kinds of ground vehicles and their systems in various driving environment conditions, (iv) design of mechatronic chassis components. Individuals from non-academic sectors seconded to academic partners are being exposed to recent knowledge in scientific methods on vehicle system modelling and control. Fig. 2 specifies several channels of knowledge sharing through secondments (staff exchanges) between the project partners. The proposed combination of research, development and training processes results in new ICC and related vehicle systems and testing procedures, which are discussed in subsequent sections.

V. INTEGRATED CHASSIS CONTROL OF VEHICLE DEMONSTRATOR

The training activities under discussion led to the concept of the target vehicle demonstrator shown on Fig. 3. This concept was firstly introduced in [8] and includes three mechatronic systems.

The functions of the *brake torque controller* cover the base brake and wheel slip control and are realized for a decoupled electro-hydraulic brake-by-wire system. Such system has the brake pedal travel sensor to measure the driver's brake demand p_{br_dem} , which is then processed in the brake torque controller to estimate individual brake pressure p_{br_est} for each calliper in accordance with actual operational conditions. To emulate the brake pedal feel, the embedded pedal simulator provides the force feedback to the driver.

Fig. 3. Concept of vehicle demonstrator with ICC for three mechatronic subsystems

The *vertical dynamics control system (VeDCS)* is equipped with sensors measuring the vertical accelerations ($\ddot{z} = dz/dt/dt$) and dampers adapting the vertical forces F_z on wheels to actual operation conditions through control of the voltage V_s . The VeDCS logic is defined by the *vertical dynamics controller*. The actuation dynamics takes into account both actual surface conditions (roughness, pavement characteristics) and the vehicle maneuver.

The *tyre pressure control system (TPCS)* dynamically inflates and deflates the tyre pressure during the vehicle motion individually on each tyre. The system consists of four tyre pressure sensors p_i , inlet/outlet valves, and the air compressor / pressure reservoirs. The *tyre pressure controller* initiates the pressure increase or decrease depending on actual maneuver conditions. For instance, the TPCS can be triggered with (i) the brake control to adjust the pressure in accordance with the surface friction and (ii) the suspension control to change the pressure in accordance with the surface roughness.

Three introduced systems are being managed by the integrated chassis controller consisting of the reference vehicle model, the vehicle state observer and the supervisory control allocation responsible for the integration of all systems.

The vehicle demonstrator with ICC components, Fig. 4, is subjected to various test procedures. The relevant experimental activities for testing the functionality of ICC are accompanied with a set of training stages having both engineering and educational character. The corresponding approaches are overviewed next.

Fig. 4. Vehicle demonstrator

VI. TRAINING THROUGH TESTING PROCEDURES

A. Integrated hardware-in-the-loop tests

The first series of testing procedures, which are required for ICC design, includes various experiments using the hardware-in-the-loop platform. For this purpose, an integrated HIL test rig on the basis of dSPACE ds1006 processor board is implemented in the EVE project. The test rig has a flexible configuration allowing inclusion of different hardware components of active chassis systems. Fig. 5 shows a variant of test rig configuration with the brake system and the tyre pressure control. In this case both systems are operating simultaneously in accordance with the vehicle dynamics and vehicle manoeuvre emulated by the real-time vehicle model. The components ds1006, ds2002, ds 2101, ds 4004, and ds 4302 on Fig. 5 are dSPACE boards for data acquisition, signal processing and actuator control.

The main training tasks related to HIL experiments are as follows:

- Feasibility check for real-time tyre models to be used in the ICC and individual controllers;
- Development and validation of real-time multibody vehicle models and benchmarking of different software applications for their realization;

Functional validation of the integrated controller as well as individual controllers of active chassis systems.

Fig. 5. Architecture of integrated HIL test rig.

The latest training task is of high importance for the project activities because it makes possible the comparative analysis of several controllers strategies developed by different research teams in order to select an optimal control architecture for the

final realization on the vehicle demonstrator. In particular, for the purposes of the braking, tyre pressure and vertical dynamics control systems, the consortium investigated a set of strategies based on rule-based, PI, sliding mode and fuzzy control. Such benchmarking is also useful for industrial developers to make proper selection of actuators and to take into account influence on-board communication, e.g. CAN, on the control performance.

B. X-in-the-loop tests

The use of stand-alone HIL solutions constrains the validation of integrated chassis control because of limited possibility to emulate many operational factors and disturbances in real-time model. A possible solution in this regard is the coupling of the HIL platform with simulators and test rigs from other domains, for example, with dynamometers, driving simulators et al. This approach, also called X-in-the-Loop, can be explained by the example of Fig. 6. Following the scheme from Fig. 6, the XIL approach is dealing with a flexible architecture allowing integration of software-in-the-loop (SIL), model-in-the-loop (MIL), HIL, and test-rig-in-the-loop (TRIL) applications. Of special importance is the TRIL part of concept that unites different setups for testing full scale objects. More information about the TRIL can be found in [9].

All the XIL components are subjected to real-time holistic networking that allows designing experiments, which are not possible in the case of stand-alone use of test rigs or simulators. It can be complex test scenarios with simultaneous investigations of the control performance of vehicle systems, wearing processes in chassis components, and the driving comfort. The corresponding example is given on Fig. 7, where the XIL approach is applied for the coupling of the HIL brake component test rig, the brake dynamometer and the real vehicle simulator (i) to define experimentally the influence of the hydraulic system dynamics on the braking control performance and (ii) to assess tribological processes as particle emission and NVH in the brakes under various braking manoeuvres.

The XIL test approach opens a number of training options, which are being used by the collaborative engineering:

- Transfer of knowledge regarding design of experiments for different physical domains, e.g. for ECU tests, tribological investigations, performance tests et al.;
- Benchmarking of diverse communication protocols (UDP, CAN, Ethernet, FlexRay) that can be used for real-time coupling of test rigs, electronic control units, and software simulators;
- Analysis of influence of automotive mechatronic systems control both on primary indicators of vehicle dynamics and secondary indicators as NVH or wear in chassis elements.

C. Distributed tests

The XIL experiments, described in previous section, can be organized when the required test equipment are concentrated in the same physical location. However, availability of test setups at different hosts opens the possibility for another approach that can be called as distributed testing.

Fig. 6. Example of X-in-the-loop architecture. RTC – real-time controller

Fig. 7. Use case of XIL coupling of brake test rigs

The concept of distributed testing is motivated by the fact that collaborating partners can have unique test facilities, and their real-time or synchronous operation under the same test specification (loading mode, vehicle maneuver, emulated environmental conditions) can be mutually complementary for investigations on complex processes.

Fig. 8 introduces the use case of distributed testing that is under realization in the framework of the EVE project and connects specific test facilities by partners from EU and South Africa. Test setups in different locations are being coupled through I/O Ethernet bus and the host PC is responsible for co-

simulation or integrated control of vehicle subsystems in real-time modus. In some cases full real-time integration may not be possible due to bandwidth and physical distance limitations. In these cases a technique of simultaneous optimisation is proposed. This will use a formal gradient-based mathematical optimisation technique using (i) the test rig at the first location to obtain gradient information and (ii) vehicle system tests at the second location to obtain accurate objective function values that can be used in the optimisation algorithms. The presented use case has some surmountable limitations caused by the wireless connection performance. The authors plan a more detailed discussion of this topic in subsequent publications.

Fig. 8. Specification of use-case for real-time integration of test rigs at University of Pretoria (UP) and Technische Universität Ilmenau (TUIL)

This approach gives additional training effect for participating staff:

- Transfer of knowledge and hand-to-hand expertise in organization of optimal validation and testing procedures in the form of remote experiments;
- Improvement of skills in modern IT technologies on advanced level, in particular, in application of “Internet of Things” approaches to complex environments for mechatronic system testing.

VII. CONCLUDING REMARKS

This work presented some outcomes of collaborative development of integrated chassis control by way of intersectoral and international training of researchers and engineers. It was illustrated that the designing of automotive mechatronic systems has a strong demand on interdisciplinary analytical and practical knowledge, and collaborative engineering with learning elements can bring benefits both for academic and industrial staff. The following main benefits can be mentioned in this regard:

- Synergetic effect from integration of academic and industrial research processes;
- Easier access to state-of-the-art and advanced experimental facilities;
- Reduced time for validation and verification of new models and controllers;
- Gaining experience in project-based research at different educational environments and industrial production systems.

An essential feature of the introduced collaborative engineering procedures is that all developed objects as controllers, demonstrators and corresponding test facilities remain fully accessible also in long-term outlook. It gives a basis for the further use and advancement of these tools in

lifelong learning activities at participating organizations and their professional networks.

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