Rolling Labs – Teaching Vehicle Electronics from the Beginning

https://doi.org/10.3991/ijep.v9i1.9241

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Abstract—This paper describes the pedagogical approach to teach vehicle electronics at the University of Applied Science Aachen. As vehicle electronics is getting more and more complex, in particular with regard to Advanced Driver Assistance Systems and autonomous driving, a dedicated concept is needed to integrate the requirements of vehicle electronics into the studies of electrical engineering. The concept of rolling labs is established during the last years for the studies of electrical engineering. The rolling labs cover different levels of complexity and integration of the electronics and components used in modern applications and hence undergraduate students can start working with interesting and close to reality systems rather early. The rolling labs enable several different possibilities of teaching and learning, either for standard labs, for team works in terms of problem-based learning (PBL) or for individual works like bachelor or master thesis. In addition, the systems can be used as research platforms and for demonstration and marketing purpose to introduce the challenging topic of vehicle electronics to other people.

Keywords—Vehicle electronics, problem based learning, lab work, advanced driver assistant system, autonomous driving

1 Introduction

Electrification, digitalization and IT are the main innovation drivers in modern cars, both for electric and hybrid vehicles (HEV/EV) and for all kind of advanced driver assistance systems (ADAS) up to autonomous driving. To realize these new applications vehicle electronics is getting more and more complex and the part of software and artificial intelligence (AI) is emerging strongly, as a short look in a modern car shows:

The functions provided by the car are realized either by dedicated systems or by collaboration of different systems. Up to 100 ECUs (Electronic Control Unit) serve as the computational power units to realize the numerous systems, from simple window lifter to very complex autonomous driving functions. Fig. 1 depicts a simple schematic for some automotive system including the embedded hardware and software, sensors, actuators and communication lines. Besides the standalone functionalities of the components the interaction and interferences of the components are essential to realize sophisticated applications.

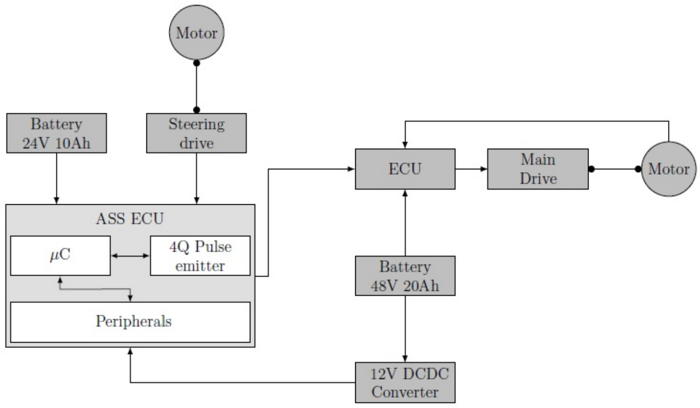

Fig. 1. Schematic of electric system of the autonomous Quad MQOne [1]

1.1 Hardware

The hardware of these embedded systems consists of logic devices like microcontroller or processor as well as of dedicated ICs, analog devices like resistors and capacitors and power electronics (Fig. 1). In general, the components of the hardware are bundled on a printed circuit board (PCB) and together they build the ECU of the system. The microcontroller is the heart of the ECU and mainly determines the processing power for the embedded software. A detailed knowledge of microcontroller with emphasis on automotive applications is therefore essential for each system. This knowledge includes the microcontroller hardware as well as programming skills (refer to chapter 1.3) and tools. The microcontroller itself interacts with other components like sensors and actuators or other ECUs. This communication can be realized via simple analog wiring or complex bus systems. For data exchange between the ECUs and the realization of enhanced functions by distributed systems a powerful digital communication is required using bus systems like CAN or Ethernet. Besides the internal connectivity the car it is also connected to the outer world, e.g. via cellular radio.

Additionally to this functional aspects automotive electronics has to meet extended environmental requirements such as temperature, vibration, power grid stability and EMC.

1.2 Sensors and Actuators

Sensors are used to collect data and parameters needed for the realization of control systems. Sensors are already used in many automotive systems, but with regard to ADAS and autonomous driving many new sensors are entering the car, e.g. camera, radar and ultrasonic sensors monitor the environment of the car for systems like Adaptive Cruise Control (ACC), park pilot or lane assist. To handle the huge amount of data, e.g. from the radar sensor, both an efficient communication system and a powerful computational hardware are needed.

Besides the main actuator in a car, the powertrain, there are plenty of actuators running in modern cars. These can be subdivided into capacitive and inductive type actuators. In particular any kind of electric motor like DC motor, PMSM or asynchronous motors are used.

1.3 Software

The software running on the embedded hardware provides the functionalities needed, starting from basic control algorithms up to highly sophisticated software for artificial intelligence. The software can be split into several part, like low level drivers, middleware or high level application software up to artificial intelligence systems. Besides the programming of the software, either using C/C++ or model based design tools are important for reliable and efficient programming. Beside of the software itself also the knowledge of automotive specific software development processes, tools and standards is gained by using them in the labs and during the projects. Especially the tool competence is an important additional skill for graduates, when applying for their first jobs.

2 Challenges and Concept

For the education of students the increasing complexity and interdisciplinary of vehicle electronics is a rather big challenge. There are more and more complex applications in modern cars with a large variety of development tools. On the other hand there are students just starting their engineering career. Therefor the main research questions of this paper are:

- How to close the gap from basic engineering education to real life automotive systems
- How to motivate undergraduate students towards vehicle electronics
- How to include the work with complex automotive systems into the existing curriculum of electrical engineering study program at UAS Aachen
- How to include team work and problem based learning (PBL) into the curriculum of vehicle electronics

Just take the studies of electrical engineering at the University of Applied Science Aachen as an example. In total the complete bachelor course lasts 7 semesters. The first three semesters of the bachelor are used for basic courses like mathematics, physic, electrical engineering or control theory. Here all the fundamentals are taught that are needed later on. The sixth semester is an internship at an external company and during the last semester of the bachelor the students work on their bachelor thesis, either internally or externally with a company. The master program lasts for 3 semesters including one semester for the master thesis.

As listed in Tab. 1 there are many technical topics that should be included in the studies of vehicle electronics. Of course, most of these topics can be covered during the lectures and labs of the general curriculum. Even though these lectures also include a lab part, these labs just focus mainly on the single technical topic only. The overall picture of vehicle electronics and systems is hard to get in this way. Besides these technical challenges soft skills like team work, communication or development processes are essential prerequisites for future engineers. Here a PBL approach is very suitable to combine the technical with non-technical aspects.

Summarizing these requirements, it becomes obvious that the education in the field of vehicle electronics needs some training on the car. But working on cars with official approval and homologation for road service is a difficult task, in particular with students who shall work on their own or in self-organized teams. E.g. live working with HEV/EV is dangerous due to high voltage and only suitable for higher level students (if at all), not for undergraduates. Also the electronics and communication of the cars is very complex and most information are not provided by the OEMs.

Current solutions for teaching vehicle electronics focus mainly on single systems and functions, like professional education systems (e.g. by [2]) or dedicated developments from research departments [3]. Even though these systems serve their purpose of teaching single systems very well, they do not focus on the complete car and do not provide a continuous way towards complete vehicle systems.

Whereas the available training systems focus on the technical part of dedicated systems, they in general do not offer the possibility of PBL or intense teamwork. PBL is part of many teaching activities for electrical engineering. This integration includes single courses [4], [5], enrichment programs [6] as well as complete curricula [7].

The basic idea for the rolling labs is to provide hands-on experiences for the students throughout the study program of electrical engineering to include PBL activities into the existing curriculum. These hands-on experiences should not be limited to single courses or topics but should act as a consecutive path for the students towards complex vehicle systems.

2.1 Concept of Rolling Labs

The rolling labs can serve as a step-by-step approach towards a training on the car to address the research questions given above. The rolling labs offer the chance to combine technical education in different complexity levels with pedagogical concepts and works. The complexity of the rolling labs increases form simple and small ECU cars to complex autonomous E-Kart and real street vehicles. By introduction of rolling projects in a rather early stage and the consecutive and more complex labs a high motivation of the students is achieved.

Each of the rolling labs serves for several different purposes. The initial task is the development of the rolling labs. Depending on the size, the complexity and the components the development is split into several smaller projects, e.g. development of the electric power steering for the E-Kart [6]. These initial developments are done either by students performing their bachelor or master thesis or by student teams in terms of PBL. A well-defined project is handled by self-organized student teams of up to 5 members with some coaching of a supervisor. The teams have the freedom and the responsibility to find own solutions and to bring the project to a result. Even failures and non-optimal solutions are possible by this approach but are accepted as part of the PBL approach. In case several teams are working in parallel on the same rolling lab also an inter-project communication and alignment is required.

After the initial development the rolling labs are used in standard courses for direct teaching purpose, e.g. in lab works. But these platform can also be continuously further developed. New projects can be defined to add additional features and systems and to improve the performance. In addition the systems can serve as research platforms in collaboration with other groups and disciplines. In this manner the Quad is now used by computer science researchers to develop localization and navigation strategies for autonomous driving in particular environments.

Initially planned for the students of electrical engineering, the rolling labs are also open for students of other disciplines, like mechatronics or computer science emphasizing the multidisciplinary of the subject.

3 Rolling Labs

3.1 Model cars

Model cars are small and simple electric vehicles like depicted in Fig. 2. These vehicles are built of just few main parts like the chassis including wheels, the electric powertrain including power supply, electric steering, some simple sensors and a small ECU. As the complexity is low it is an excellent starting point for several projects and courses.

As an example the model car depicted in Fig. 2 was developed by a student team (4 students of 4th semester) during a one semester project work. This project included the following tasks:

- Project management
- Hardware development
- Software development
- Mechanical construction
- Development of the electric powertrain
- Control algorithms
- Application development (follow the white line)

The students worked in a self-organized project team including a project management, reporting and budget planning. After the general project setup a concept was developed in a top down manner, from the given requirements to the detailed realization of the hard- and software.

The PCB was designed using Altium Designer, a state-of-the-art electronic design automation software for PCBs. Two Renesas microcontrollers (RX and RL78 family) were used for motor control and application software respectively. These microcontrollers are commonly used in industrial as well as automotive applications and are programmed in C using Renesas' proprietary IDE e2studio. The mechanical design was done with Catia V5, a standard CAD software.

Using model cars like the one described above several teams were able to take part in the Renesas MCU Car Rally during the Embedded World Conference 2015 and 2016 [2]. During this challenges teams from all over Europe compete in a race of self-programmed model cars following the with line of a 77 m racing track. In 2016 the team of UAS Aachen finished 5th.

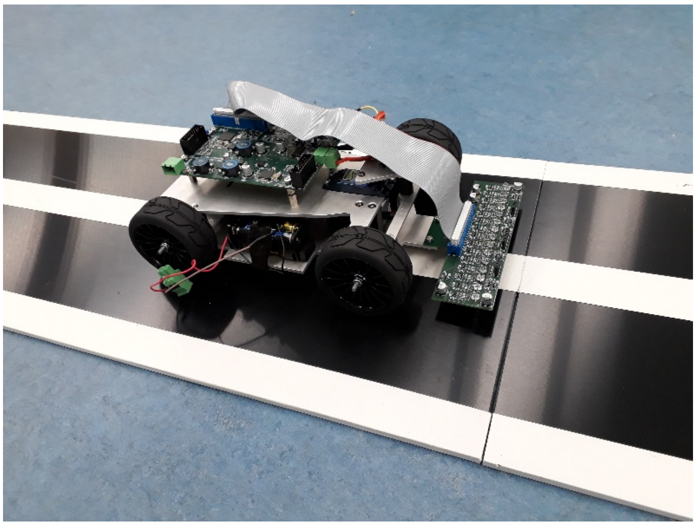

Fig. 2. Model car on test track

After the development of this basic vehicle it now serves as a platform for further labs and new projects. Students gain experience in programming state-of-the-art microcontroller and embedded control algorithms.

3.2 E-Quad

The autonomous electric quad was developed in collaboration with colleagues from computer science of the UAS Aachen [1]. The idea was to develop a robust, easy to handle and cheap prototype for the development of localization and navigation applications in particular environments, e.g. mines. To make life as simple as possible for the computer scientists the concept was to separate the hardware related development from the higher level software-based intelligence, which uses sensors like radar or laser scanners to get an image of the quad's environment. Based on the environmental data it calculates its location and path and sends both the speed and the steering angle setpoints to the hardware control of the quad via a simple USB connection. Form the hardware control it receives the actual speed and steering angle for the motion control algorithms.

The starting point was an S-8 Farmer Electro 1000 Watt quad, a full electric quad for children. Its 1 kW traction motor is running on a 48 V battery with a capacity of 20

Ah resulting in a 1 h full speed operation time. The traction motor provides a mechanical power of about 0.75 kW at the rear axis. The speed and the braking are originally controlled manually by the accelerator and braking at the handle grip. These manual controls were disconnected and the control voltage for the motor controller is now generated by a central ECU instead. During two master thesis the required basic functionalities to achieve autonomous driving were added to the quad: the electric power steering (EPS) including the central ECU and an electric braking system (Fig. 3).

The development of the EPS started with the mechanical design. Based on a required torque analysis a motor-gearing combination was selected and mounted to the quad. The connection to the steering column was done by a belt. For position control of the steering column a magnetic angle sensor was used. For the control of the EPS as well as for overall system control a central ECU was developed using a STM32F407VG microcontroller from STMicroelectronics (Fig. 1). Running at 168 MHz its ARM Cortex M4 CPU with integrated FPU (Floating Point Unit) provides the needed calculation power for the control of the quad. Altium Designer was again used for the PCB design. For safety reasons, a wireless emergency stop switch is integrated to disconnect the motor from the power supply in case of an emergency [3].

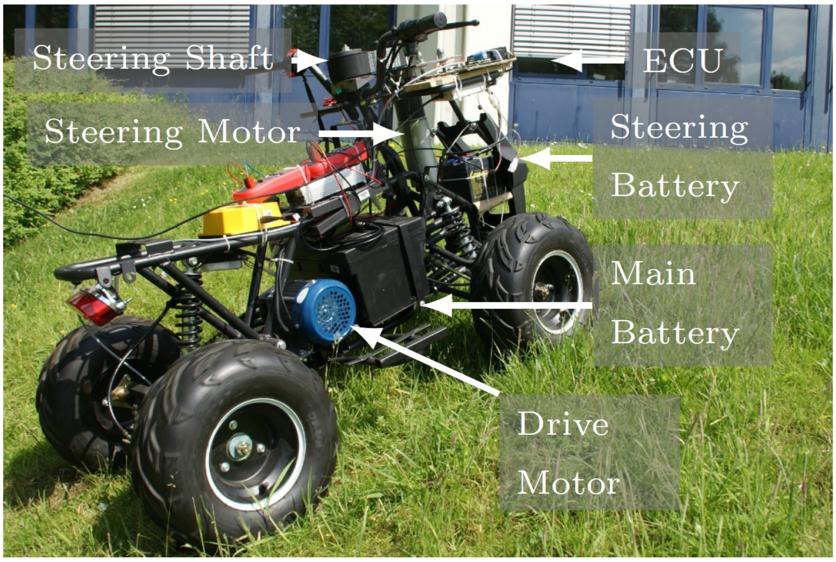

Fig. 3. Main components of the E-Quad

To keep the hydraulic braking system an electronic actuator is used to apply the required pressure to the brakes. Here a clutch actuator by FTE provides a pressure of up to 24 bar. It is controlled via CAN bus by a separate braking ECU which uses again the STM32F407VG microcontroller. Using a second CAN interface this ECU communicates with the EPS ECU and the higher level logic to get the required braking data and to provide feedback itself. For the connection to the higher level logic a USB-to-CAN adapter is used (Fig. 4). CAN matrices were set up for proper communication [4].

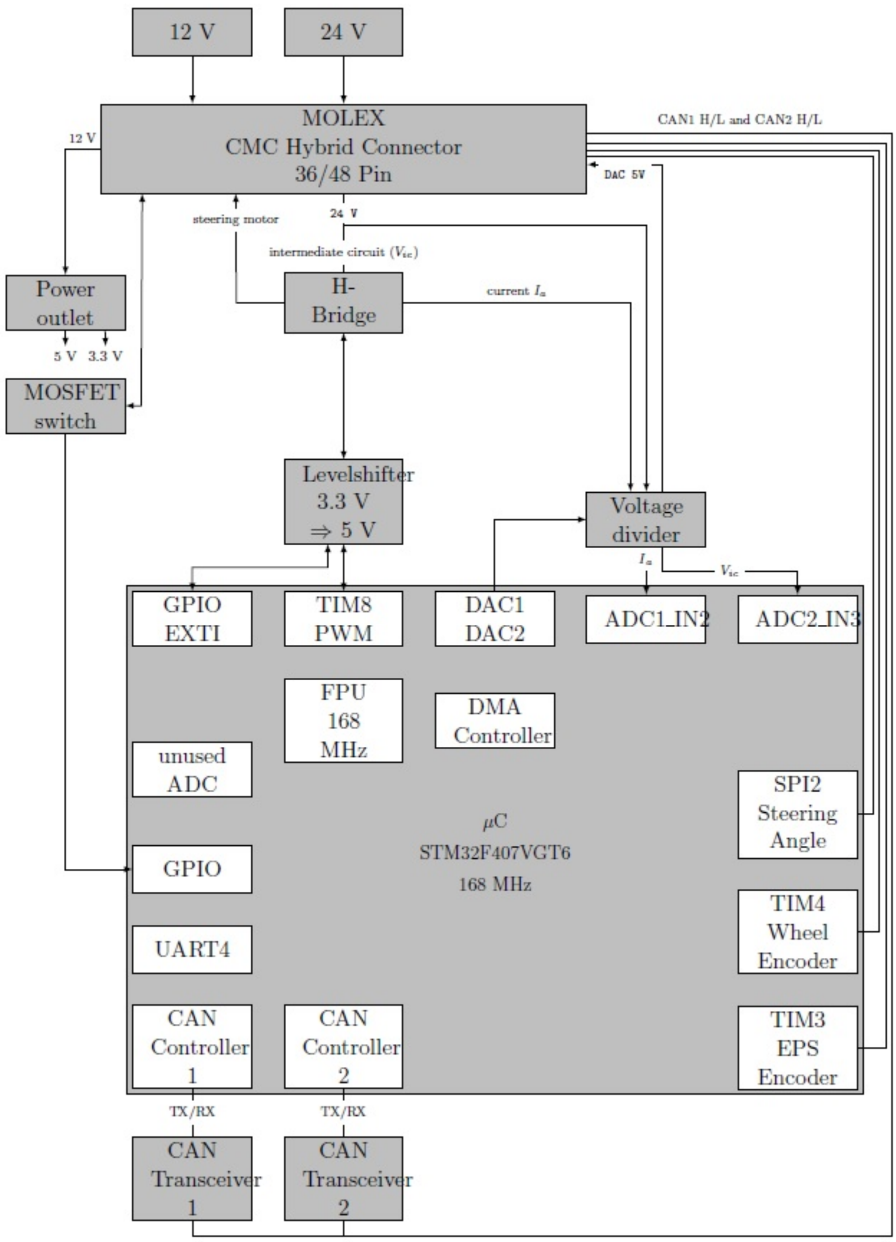

Fig. 4. ECU of the E-Quad [1]

Overall, the main tasks for the development of the quad included:

- Hardware development including mechanic and hydraulic construction
- Software development

- Mechanical construction
- Control algorithms
- Data communication via CAN
- Use of typical CAN development tools like Vector CANalyzer

After successful initial tests the quad was forwarded to the computer scientists for application development for autonomous driving. In 2016 it showed its capabilities during the Aachen 2025 demo event driving autonomously. It now serves as a demo object for students to show basic concepts of vehicle systems, data communication, sensors and autonomous driving algorithms as well as for future projects. These future projects include application development for advanced driver assistant systems (ADAS) up to autonomous driving functions.

3.3 E-Kart

A similar approach like the E-Quad is followed by the E-Kart project, but there are some major differences in the concept and the targets of the E-Kart. In the Quad project there is a dedicated separation between the low-level hardware part and the higher-level intelligence. For the E-Kart there is no such separation, instead the overall system architecture is closer to the real automotive world. Besides the chassis all systems of the kart were developed from scratch by several student teams in a PBL approach or students during their thesis. Development projects during the last years:

- Vehicle power supply including electrical motor, battery and cable harness
- Electric power steering [6]
- Electric braking
- Sensor cluster including Lidar, stereo camera, IMU, wheel sensors
- dSpace MicroAutoBox II as central control system
- Hard- and Software architecture for autonomous operation [5]

Fig. 5 depicts the hardware architecture of the E-Kart including the sensors and actuators. A 5.5 kW permanent magnetized synchronous motor (PMSM) is able to speed the kart up to approximately 55 km/h. The motor is driven by a SEVCON inverter running at 48 V that are supplied by a LiIon battery pack of 100 Ah capacity. The braking system is designed similar to the braking system of the E-Quad, using a FTE clutch actuator to supply the hydraulic pressure to the hydraulic brakes at the rear axis. For the EPS a MAXON DC motor is used that is driven by an EPOS controller. An absolute position sensor is used to measure the actual steering angle [6].

Central control element for the E-Kart is a dSPACE MicroAutoBox II (MAB II), a real time system for rapid control prototyping systems, which is widely used in the automotive industry. Here the preprocessed input data from the sensors are collected and analyzed and the actuators are driven according to the control algorithms. These control algorithms are developed in Matlab®/Simulink® and therefore it is possible to cover the complete flow of model based design starting from Model-In-the-Loop simulations over autogenerated C-Code up to calibration by using industries standard tools like dSPACE ControlDesk NG (CDNG).

Main communication system of the EKart is again a CAN bus, but also Ethernet and USB are used for communication of the Lidar sensor and stereo camera and IMU (Inertial Measurement Unit) respectively. A USB hub serves as a gateway from the stereo camera and IMU to a preprocessing unit. This preprocessing unit can be an x86 hardware or a Jetson TX 2 board from NVIDIA as both systems provide the required computational power to process the large amount of data [5].

Using all these systems the E-Kart can be operated in different modes. Currently there are two modes, manual operation by a driver and RC control. Manual test drives proved the maximal speed of about 55 km/h and a highly dynamic steering behavior. Initial RC controller test drives of the E-Kart took place at the kart center in Eupen. During these tests sensor data were collected for offline processing and initial validation of the data.

Based on the current status of the E-Kart it now serves as a mobile research platform for different topics as well as lab for education of vehicle electronics, sensors and hard- and software architectures for autonomous driving. Currently several groups extend the functionalities and systems of the E-Kart. E.g. one group integrated a radar sensor for object detection and a second group develops a model of the driving dynamics of the E-Kart. Using the results of these groups will make an autonomous driving of the E-Kart finally possible.

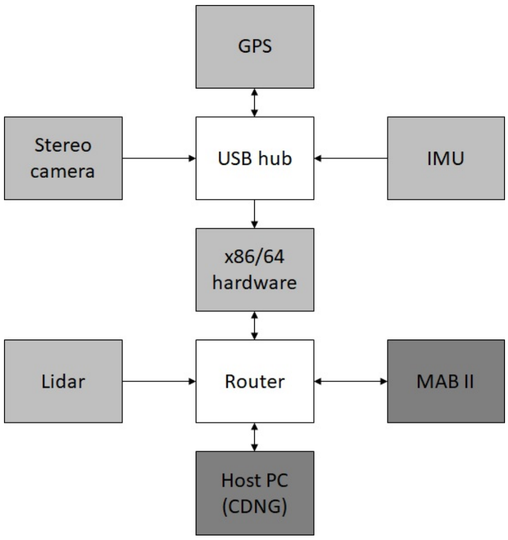

Fig. 5. Schematic of the hardware architecture of the E-Kart

3.4 Road vehicles

Working with real cars is of course essential for any student in the field of vehicle electronics. Therefor the final stage of expansion for the rolling labs are different kinds of road vehicles. These cars enable the study of state-of-the-art commercial systems with emphasis on standard vehicle electronics, electric powertrains and advanced driver assistance systems.

An Audi A3 serves as a real life lab for standard vehicle electronics. Here students can measure electrical parameters of different systems and components, like ignition plug or variation of the electrical power supply network voltage due to different load conditions. The results are discussed and analyzed with regard to corresponding norms and specifications. Also topics like OBD (On-Board diagnostics) can be done to get a deeper insight into the embedded systems of the combustion engine.

During a student project the powertrain of a Smart Four Two was converted from combustion engine to an electric drive. The conversion was done by six students during a one week session in a garage. They removed all the parts of the combustion engine and integrated the components of the electric powertrain including battery, electric motor, inverter, charger and the electrification of auxiliaries like the vacuum pump for the braking system. A 20 kW asynchronous motor is attached to the original gearbox that is fixed to the second gear. This enables a top speed of about 80 km/h and together with the 18 kWh, 100 V LiIon battery a range of about 80 km. After the conversion the electric vehicle received the official approval and homologation for road service.

The electric Smart is now used for teaching purpose in the field of electric vehicles. First of all it provides the possibility for students to drive electrically and to experience the pros and cons of electric vehicles. In addition they get insights into the architectures of electric vehicles and learn to work in high voltage systems.

Several projects were also done with the smart to extend its features and systems:

- Optimization of the powertrain with regard to control of the asynchronous motor, recuperation and driving dynamics [8]
- Development of a hardware for charging control [7]
- Development of a CAN-to-Wifi board for transmission of vehicle data [9]
- Integration of a tablet computer as main infotainment system

Fig. 6. Conversion of the Smart to an E-Smart: new harness (left) and E-Smart after official approval (right)

In an additional student project with electronic engineering and computer science students a KIA Niro was modified to be able to be remotely controlled. Due to this modification driving pedal, brake and steering can be controlled by an additional computer system. This makes the car ready to extend it by own longitudinal and lateral control systems, which will be also developed in student projects.

Fig. 7. Converting a KIA Niro (photos: FH Aachen, Daniel Fink)

In the near future the KIA Niro will be equipped by many additional sensors like radar, lidar and cameras to convert it into a fully autonomous driving car. This makes it an ideal platform for education and student research on sensor fusion, localization and deep learning algorithms based on artificial intelligence. Because safety is always a big issue, when working on real cars, the Niro is always operated with a safety driver, who is able to take over control at any time just by touching the driving pedal, brake or steering wheel.

All these projects have to be done in a way that the car keeps its official approval. In subsequent projects additional advanced driver assistance systems will be added, like a rear view camera and sophisticated range calculation based on real drive energy consumption and driving prediction. Together with other departments also features like connection to the cloud and similar will be added.

4 Discussion

With the concept of rolling labs the UAS Aachen established a kind of bottom-up approach for teaching students of electrical engineering in vehicle electronics. Tab. 1 depicts the technical topics that are covered by the different rolling labs, both for the development phase and the use in future lab works. The development covered many of the technical topics for each dedicated rolling lab. These developments provide a high degree of sustainability with regard to future use. All rolling labs are used for further education of technical topics.

The development of the rolling labs was done in a PBL approach by several groups and students, either in form of team work or during bachelor and master thesis (Tab. 2). More than 60 students were involve in the development of the labs. During their work they experienced a high degree of freedom in finding their own solutions, accompanied by detailed technical discussions. They also gained a lot of experience in engineering work, both in technical and non-technical topics. The technical topics covered for example simulation, electrical design, embedded software, mechanical construction and failure analysis. Non-technical topics were project work, reporting, documentation, presentations and discussions.

Table 1. Important technical topics of vehicle electronics and main correlations to rolling labs

Topic	Development phase				Further use in education			
	Model Cars	*Quad*	*E-Kart*	*Cars*	*Model Cars*	*Quad*	*E-Kart*	*Cars*
Hardware	X	X	X	X			X	X
Mechanics	X	X	X			X	X	X
Microcontroller	X	X	X		X			
Connectivity		X	X	X		X	X	X
Software	X	X	X	X	X	X	X	X
Control theory	X	X	X	X	X	X	X	X
Development tools		X	X	X		X	X	X
Sensors	X		X	X	X		X	X
Actuators	X	X	X				X	
Driving experience			X	X			X	X

As can be seen in Tab. 2 the cost for the development of the rolling labs increase significantly, from about 1.000 € for the small model cars up to more than 40.000 € for the E-Kart and the Kia Niro. These high costs have to be covered and they are for sure a strong counter-argument for this kind of lab. On the other hand this approach provides the highest degree of flexibility, complexity and opportunities for the education of students.

Even though the students and groups worked in a highly self-organized way the efforts for supervision of the many projects is rather high. Weekly or biweekly meetings, specifications, discussions and technical as well as non-technical guidance takes a lot of time for the supervisor. The effort is far beyond the effort for standard courses, but again, the educational and technical outcome for the students justifies these efforts to be spent.

Table 2. PBL approach for the development

Rolling lab	Number of project groups so far	Number of thesis so far	Approx. cost so far
Model cars	4	0	1.000 €
E-Quad	1	3	3.000 €
E-Kart	7	2	> 40.000 €
E-Smart	1	4	30.000 €
Kia Niro	1	1	> 40.000€

Besides the projects for the development of the rolling labs they are also used in courses of the curriculum of electrical engineering and computer science as depicted in Tab. 3. All rolling labs can be used for teaching purpose in any stage their development. As the functionality and the systems can be modified and extended in a flexible way, it is possible to keep the labs up-to-date by subsequent student projects. Therefore these labs have a high degree of sustainability in terms of long and intense use.

Table 3. Integration of the rolling labs in the curriculum of vehicle electronics at UAS Aachen

	Term	Rolling labs	Course examples
Bachelor	1-3	All	Demonstrators for basic courses
	4	Model cars, E-Kart, E-Smart, Hybrid Niro	Vehicle electronics, vehicle systems, vehicle software
	5	E-Kart, E-Quad, E-Smart, Hybrid Niro	Sensors and actuators, data bus systems, EMC
Master	>7	E-Kart, E-Quad, E-Smart, Hybrid Niro	Electromobility, Functional Safety

In addition to the electrical engineering courses, the rolling labs are also used for interdisciplinary projects in conjunction with information technology, robotics and artificial intelligence. This collaboration takes the strong interconnection of electronics and high-level software in modern cars into account. Furthermore students of the multimedia study at UAS Aachen (Media and Communications for Digital Business) joined the developments of the rolling labs to produce educational films and video documentations.

Compared to other solutions like systems by [2] or [3] the rolling labs provide a continuous way to teach vehicle electronics throughout the curriculum. This step-by-step approach towards real cars enables students to experience vehicle electronics in a rather early stage of the education and keeps the motivation until the final stages of the bachelor and master program.

At UAS Aachen all courses and projects are evaluated after their finalization. The evaluation of the several development projects revealed an excellent feedback from the students. In particular the self-organization and PBL approach were highly appreciated as they introduce a new pedagogical concept to the vehicle electronics. This positive feedback also includes the experience of facing and solving technical as well as non-technical problems and drawbacks. As an example the following list shows some feedback of a course about autonomous driving at UAS Aachen during the summer term 2018 (all rating on a scale from 1 (excellent) to 5 (poor):

- Overall rating: 1.25
- Relevance of topic: 1.46
- Learning environment: 1.15
- Lab work: 1.42

Further written comments emphasized the practical approach ("praktische Umsetzung", "Praxisbezug", "selbständiges Arbeiten") as well as the multidisciplinarity ("Mix von Studenten unterschiedlicher Fachrichtungen") and the team work ("Gruppenarbeit").

After the students finished their academic studies to start work in industry we also get feedback, both from the former students and the industrial partners. The former confirm the good evaluation as they feel very well prepared for the work in automotive companies. The latter appreciate the ability of problem-solving and team work of the former students.

5 Conclusion and Outlook

As demonstrated, the UAS Aachen is supplementing the theoretical studies in lectures etc. by a wide range of contagiously developed rolling labs. With this approach, students are able to train their skills in individual as well as team-projects in the field of automotive electrics. By the use of rolling labs, all aspects of automotive electronics can be shown, applied, developed and researched by the students in a close to real world surrounding. Students have to merge their knowledge from a wide range of lectures to solve their problems. This course overlapping, problem based learning approach prepare the students for their career in the automotive industry in a manner, which cannot be achieved only by taught courses.

6 Acknowledgement

The development of the rolling labs was generously funded by the department of electrical engineering and information technology of UAS Aachen. A special thanks to all the students who contributed to the several projects, either during projects or the thesis. René Hess supported the multimedia-based documentation of the developments.

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Article submitted 16 July 2018. Resubmitted 26 October and 02 November 2018. Final acceptance 02 November 2018. Final version published as submitted by the authors.