ADAPTING AUTOMOTIVE ENGINEERING EDUCATION TO AUTONOMOUS DRIVING REQUIREMENTS

Peter Heidrich[1]*, Elie Jaussaud[2], Niklas Weiß[1]

[1]University of Applied Sciences Kaiserslautern, Schoenstraße 11, 67659 Kaiserslautern, Germany

[2]ECAM Strasbourg, 2 Rue de Madrid, 67300 Schiltigheim, France

Abstract

Automotive engineering education of the past was based mainly on mechanical items like chassis, powertrain and internal combustion engines. Due to powertrain transformation towards hybrid and electrical systems as well as more and more driver assistance systems including more and more sensors and actors, the electronic and IT fraction in modern cars increased over the past years from nearly nothing up to approximately 35 % of the automotive value creation chain.

Hence, the curriculum of study courses related to automotive engineering has to be endorsed with electronic and IT based course topics. This endorsement has to cover lectures and additionally laboratory exercises. Especially the laboratory exercises should be adapted to requirements of mechanical engineering students.

The conversion of laboratory exercises was very challenging, as previous knowledge of mechanical engineering students differ completely from those of electronics or informatics students. Therefore, the existing laboratory exercises has to be converted to appropriate laboratory exercises using microcontrollers as well as electrical and hybrid powertrains. New laboratory exercises from simple level like "read a sensor and control an actor" up to CAN bus communication between three controllers - all based on Arduino microcontrollers - were designed, constructed and tested with first groups of mechanical engineering students. Furthermore, laboratory exercises with a hybrid RC vehicle were established and tested. Student's feedback was used to optimize these new laboratory exercises in an educational manner.

Keywords: *Engineering Education, Mechanical Engineering, Laboratory Exercises, Microcontroller, Arduino Family, CAN Bus Communication, Hybrid Powertrain Analysis*

1. INTRODUCTION

Actual vehicles of the 21st century are no longer mainly mechanical based machinery but rather driving computer networks. They contain up to 200 electronic control units (ECU) to operate features like instrumentation, powertrain and power distribution, driver assistance systems and even organising inter-car communication of connected cars [1-3].

In the late 1970s and early 1980s first applications of ECUs were entering the vehicle market. They were mainly stand alone systems with only one or just a few – mostly redundant – sensors and mostly single actors like spark plug operation, intake manifold injection or beginning safety features like antilock braking systems. Over the years more and more ECU-driven features like thermal control of engines and cabines, exhaust gas treatment, adaptive cruise control, passive and active crash avoidance, comfort functions and last but not least traffic information and infotainment systems were implemented in the vehicles [1, 4-6]. At the same time more and more communication between single ECUs was necessary. This resulted in CAN bus development and CAN bus connection of ECUs [4, 7]. The vehicle converted from mechanical machinery to driving computer networks.

Thus, there is an immediate need to adapt automotive engineering education to these new requirements. Obsolescent teaching and learning contents – like automatic gearbox design or internal combustion engine operation – have to be replaced by actual contents – like hybrid and electrical powertrains, basic knowledge in driver assistance systems, and usage of ECUs as intelligent operator of all kind of vehicle action. To convey these new teaching and learning contents successfully, the mandatory oral lectures have to be supported by suitable laboratory exercises.

2. RELATED WORK

A first step was to conduct a widespread literature review with focus on

- teaching microcontrollers on all levels of education,
- how to combine oral lectures and laboratory exercises,
- design of suitable laboratory exercises,
- as well as commonly used software and hardware.

The earlier future students are introduced to microcontrollers, even on primary school level, the easier is the fundamental scientific teaching and learning during academic studies [8]. Additionally, nowadays all engineers – at least – should be able to understand and – in best case – should be able to program embedded systems as they are part of engineering [9]. Just remember actual key technologies like digitally networked production, smart home, autonomous driving or artificial intelligence. Furthermore, teaching microcontrollers is not only limited to schools and universities. In the field of lifelong learning industrial trainees are more and more relevant customers [10, 11].

When redesigning a curriculum the opportunity of didactical improvements should be included. Hence, oral lectures and laboratory exercises should be interlocked. Therefore, contents from the lectures should be relocated in the laboratory exercises consequently. If possible – consider confidentiality – laboratory exercises could be stimulated by incorporation with actual research work [12]. An actual trend in laboratory exercise design is project based learning [13, 14]. Instead of getting step-by-step instructions of laboratory exercises students are faced with rough descriptions of a project scheme and they should develop solutions on their own. This procedure improves their meta cognitive skills and would help them in lifelong learning [13]. Another approach with similar intents is the so-called outcome-based education [15]. Here just goals are defined and the students should design their own path towards these goals. An additional enrichment would be working in teams to improve team player skills as one of the most requested soft skill in actual job advertisements [16]. A very progressive approach for master classes is described in [17]. Here the splitting of lectures and laboratory exercises is abandoned completely. It is replaced by an interaction of short theoretical lectures – sometimes just as oral explanation in the laboratory ambient – self study periods of the students with final presentation to the public and hands-on laboratory exercises. A final perception is, that today's students – mostly born around 2000 – are digital natives with high affinity to all digital technologies. Hence, learning programming based on the traditional "hello world" approach is no longer applicable. Programming courses should be converted towards nowadays requirements [18].

Regarding used hardware there is a clear preference for the benefit of low-cost single-board computers [7]. Mostly used are microcontrollers of the Arduino family, as there are several starter kits, lots of different sensors and actors as well as corresponding libraries and last but not least an easy to handle integrated development environment (IDE) with a C-like programming language available [4, 7, 13, 16]. Some of corresponding laboratory exercises use just starter kits and included breadboards [19] while others established special experimental boards [18] or even highly developed equipment with plug-and-play wiring [10, 11, 20].

Educational activities with reference to CAN bus teaching and automotive applications show as well a strong preference for Arduino family and additional CAN bus shields [19]. More challenging laboratory exercises use either model vehicles for demonstration and analysis of CAN bus communication with close to reality test setups [18, 21] or even real automotive hardware for simulation of CAN bus communication and analysis of associated vehicle data [22, 23].

Concerning laboratory exercises with hybrid vehicles or hybrid powertrains the literature review has shown two main directions. One way is to conduct laboratory exercises with real vehicles or just extracted powertrains of real vehicles [24, 25]. Having said that recent papers show clear tendency towards modeling and simulation instead of using real hardware [26-28]. The other way is to work with – mostly radio controlled (RC) – model cars as they are cheaper, less dangerous and not as complex as real hardware is [18, 21, 29-31].

3. HARDWARE SELECTION

Out of a recapitulation of related work and an internal discussion with students, assistants and educational staff unit basic requirements or rather first specifications were made. In a next step hardware for microcontroller, CAN bus and RC vehicle exercises were specified and purchased. If necessary, built-on and adaption working was carried out.

3.1. Basic requirements

Based on the new curriculum of mechanical engineering education the decision which software to use was an easy one. As mechanical engineering students have lectures in programming based on C/C++ in the first two semesters, it is obviously to use Arduino and its IDE.

A first trial and error with an Arduino starter kit yield in unsatisfactory wiring and connectivity of the included components. Hence, the decision was made to assemble all necessary hardware, like micro-controller, sensors, actors, displays, etc., in solid caskets and use banana plugs and jacks for wiring.

From a didactical point of view, the hardware should give option to start with easy laboratory exercises, like “read an input sensor, asses its state and control an actor”. Furthermore, the hardware should be able to fulfill challenging laboratory exercises high in the grade, like “CAN bus communication between three microcontrollers”.

Regarding the provided laboratory handbooks, there should be a straight enhancement from exercise to exercise. If reasonable, there could be a classification in beginner level and advanced learner level. Hence, differences in previous knowledge could be considered easily. None of the participants should be overstrained nor be bored.

3.2. Hardware for microcontroller exercises

The Arduino platform covers more than 20 different boards with completely different configuration regarding operation voltage, memory size (Flash, EEPROM, SRAM) and I/O options (digital, analog, PWM). Regarding the designated microcontroller exercises the Arduino board Mega 2560 was chosen, as it provides enough memory capacity and a satisfying I/O configuration (54 digital, 14 PWM, 16 analog input). Furthermore, a freeware IDE is available on the Arduino homepage for download at no charge (see Fig. 1).

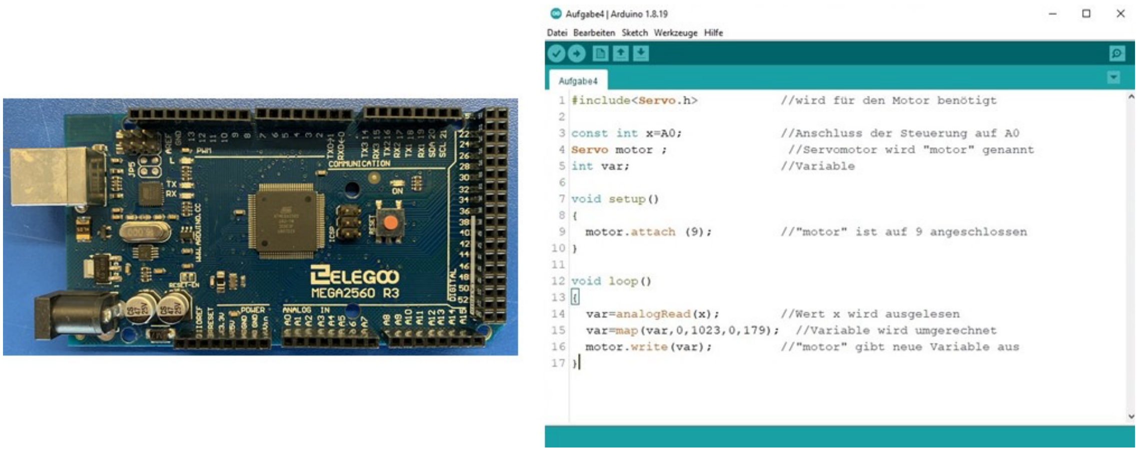

Fig. 1. Microcontroller board Arduino Mega 2560 and typical Arduino IDE

The Arduino board is embedded into an aluminium casket with acrylic glass cover plate for optical access. All necessary ports and all external connections are led through to the casket's side walls and connected with banana jacks (see Fig. 2).

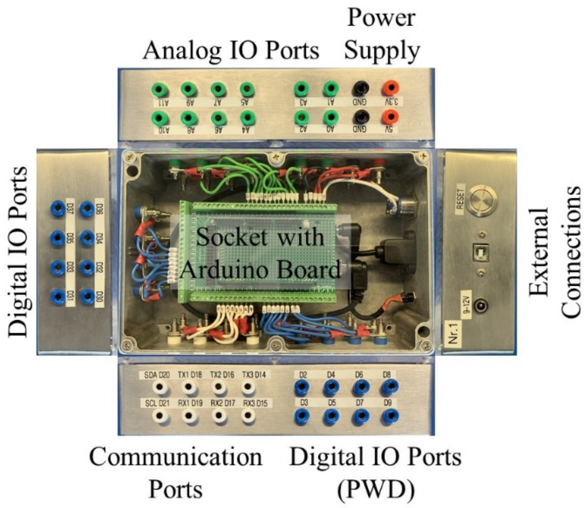

Fig. 2. Design of Arduino casket and layout of all external connections

Concerning the required sensors and actors four additional caskets are designed. One casket contains just four LEDs, two push buttons, and one potentiometer (see Fig. 3, casket Nr. 2). This casket will be used for laboratory exercises on lowest level, like "read push button and turn LED on". A casket alike contains six LEDs and one three point switch (see Fig. 3, casket Nr. 5). This casket will be used for programming and analysing of animated indicators. Another casket contains just one LCD with two lines of 16 characters each (see Fig. 3, casket Nr. 3). It will be used for simple text output. The last casket contains a two-dimensional joystick and a servo actuator with 270° pivoting range (see Fig. 3, casket Nr. 4).

Fig. 3. Set of designed sensor/actor caskets (Nr. 2 – switches and LED / Nr. 3 – LCD / Nr. 4 – joystick and servo actuator / Nr. 5 – LED panel for indicator simulation)

All sensor/actor devices are embedded into solid aluminium caskets of suitable size. All wiring is led through to the side walls again and connected to banana jacks.

For all sensors and actors, the corresponding data sheets are available in the laboratory, as they are needed for proper parametrisation of these devices during programming.

3.3. Hardware for CAN bus exercises

For CAN bus exercises a slightly different Arduino board, the Arduino Uno, was chosen, because there is less need for I/O options. As CAN bus interface the AptoFun CAN-Bus Shield MCP2515 with TJA1050 Receiver SPI Protocol was selected.

Again, both components are embedded into a common plastic casket with transparent cover plate. External connections are carried out as banana jacks, too. The number of external connections is reduced, as there will be less need for them when CAN bus exercises will be conducted. In this laboratory exercise the main focus is on CAN bus specific wiring and not on sensor/actor action. Details of the CAN bus casket and the external connections are shown in Fig. 4.

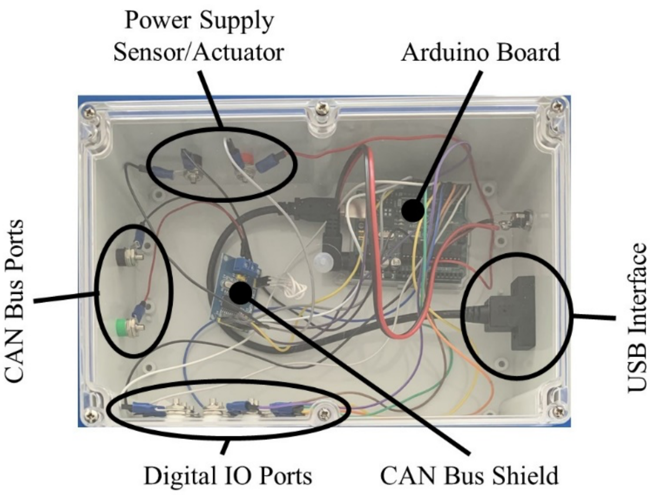

Fig. 4. Design of CAN bus casket and layout of main external connections

3.4. Hardware for RC vehicle

The main requirements regarding the RC vehicle are a hybrid powertrain of any kind and the availability of an appropriate chassis dynamometer.

A comprehensive internet search results in two main implementations. On one hand there are very simple hydrogen fuel cell-based systems with mostly none additional energy storage. They are used typically for first exercises with hydrogen in state schools or as leisure activity. On the other hand, there are more complex systems. They are based on commercial RC vehicles, mostly with lithium-ion battery as energy storage. Additionally, a hydrogen fuel cell with a suitable monitoring board is implemented [31, 32]. Furthermore, for these systems a chassis dynamomoter is available, too.

Another result of the internet search is, that there are no systems disposable with a combination of internal combustion engines and an additional electrical energy storage. Systems of this type would have been interesting, too, as they are the most common system in actual automotive applications [33, 34].

An internal discussion on which way to go resulted in the decision to purchase a fuel cell hybrid system as described in [32] and as used in [31] for research work. The system covers the requirement of a hybrid powertrain as well as it fulfills the need of a chassis dynamometer (see Fig. 5/6).

The RC vehicle is based on a 1/10 scale vehicle with permanent four wheel drive, electrical engine, electronic speed control and a lithium ion battery of 7.2 V in voltage and a capacity of 4200 mAh. Additionally, a proton exchange membrane fuel cell (PEM FC) of 30 W power output and two hydrogen storage sticks are installed. The control is done by an energy management board. Furthermore, a measurement controller unit based on Arduino Yun is implemented. This unit is used to control the braking forces of the chassis dynamometer, too (see Fig.5). The hydrogen storage sticks could be refilled easily with the corresponding electrolyser.

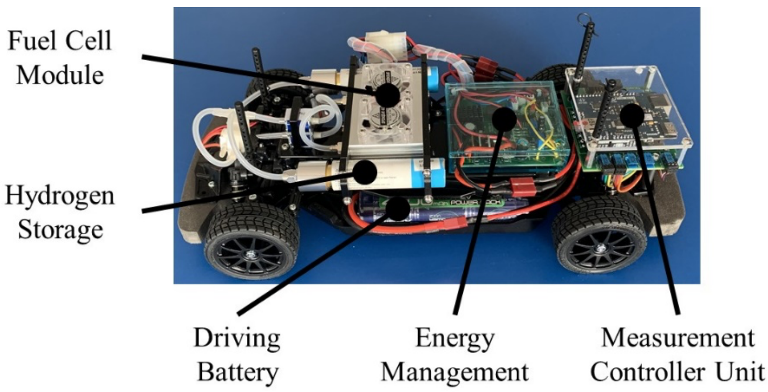

Fig. 5. RC vehicle and hybrid powertrain components

The chassis dynamometer is built of aluminum profiles. It contains two axis (front and rear) with two track rollers on each side (left and right). Both axis are coupled by a toothed belt. The braking forces are raised by a servo motor, which is controlled by the measurement controller unit. Therefore, additional wiring between these two components is necessary (see Fig. 6).

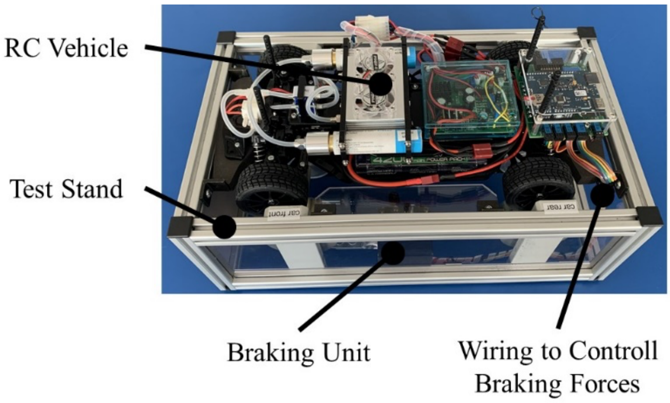

Fig. 6. RC vehicle mounted to chassis dynamometer for energy consumption measurements

Furthermore, there is an option to operate the RC vehicle without the chassis dynamometer and drive it with the corresponding remote control. Hence, there are possibilities to test the RC vehicle on different test circuits [31] and/or to participate in competitions.

4. LABORATORY EXERCISES DESIGN FOR MICROCONTROLLER AND CAN BUS TASKS

After hardware equipment is clarified, next step was to design appropriate laboratory exercises. First of all the microcontroller exercises were elaborated.

Comprising basic requirements five fundamental laboratory exercises were finalised. Each of them has a reference to automotive applications (see Tab. 1).

Exercise	Content	Reference
1	Connect laptop and Arduino, use USB, make LED shine.	---
2	Use two push buttons as sensor and enable/disable LED shining.	Lights on/of
3	Display an encoded text on an LCD, use related library in program.	Display in dashboard
4	Operate a servo motor with a joy-stick, use libraries, operate servo motor with PWM signal.	Outside mirror adjustment, electronic throttle control
5	Operate six LEDs like animated indicators, change direction with a threepoint switch, change duration of interrupt/illumination in program.	Animated indicators, hazard flash lights

Table 1. Content of fundamental laboratory exercises and related automotive applications

For each laboratory exercise a proper description with problem, needed hardware, schematic of wiring and information with regard to program architecture is prepared. For laboratory exercise 2, the complete program is provided and the students have to take care of correct wiring. With the following laboratory exercises the given specifications are reduced step by step. Hence, students have to spend more and more effort in programing. Additionally, they should find information on sensor/actor parameters in provided data sheets. An exemplary composition is shown in Fig.7.

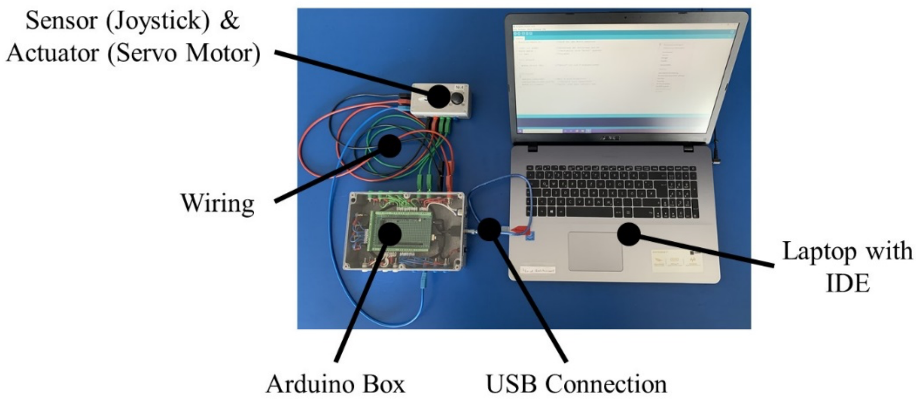

Fig. 7. Composition of representative fundamental microcontroller exercise with typical wiring

Then, all laboratory exercises were carried out by a first group of students. During the experimental procedure the group was observed and if necessary assisted. After this first testing, an internal discussion among supervisors and an additional feedback discussion with the group of students some minor adjustments in the descriptions were necessary. Additionally, the given programs were adjusted and some minor flaws were eliminated. Taken as a whole, the students felt well assisted and were neither overstrained nor bored.

Now, there was need for designing the CAN bus exercises. In this case three typical CAN bus laboratory exercises were finalised. Their contents are shown in Tab. 2.

Exercise	Content
1a	Connect two CAN bus caskets, connect each additionally to a laptop, upload given programs, start system monitors, observe sending/receiving of messages.
1b	Connect a third CAN bus casket, again with own laptop, complete upload of given programs, start system monitors, observe sending/receiving based on CAN bus ID of each device.
2	Connect two CAN bus caskets, each with own laptop, connect one CAN bus casket with LED casket, upload given programs, make LED shine by adapting LED-parameters in program.
3	Connect a third CAN bus casket, again with own laptop, connect first CAN bus casket with push button casket, connect third CAN bus casket with LCD casket and potentiometer casket, renew upload of given programs, send CAN bus message depending on push button state, observe action of receiving CAN bus caskets.

Table 2. Content of CAN bus laboratory exercises

Based on experiences from microcontroller exercises, again proper descriptions of problem, hardware and wiring are prepared. However, the wiring documentation is carried in a more schematic way (see Fig. 8/9).

Fig. 8. Wiring schematic for CAN bus exercise 1a

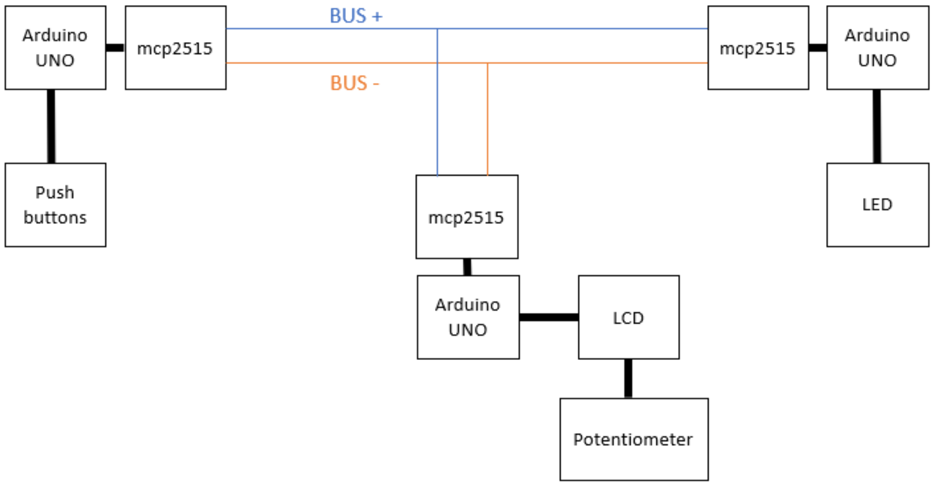

Fig. 9. Wiring schematic for CAN bus exercise 3

As the basic content of these laboratory exercises is to convey CAN bus functionality to students, all programs – sending and receiving codes as well as master/slave codes – are provided on the suitable laptops. Only adjustments in parameters like CAN bus ID, LED parameters or message texts for LCD are necessary.

First testing with one volunteer student has shown, that laboratory exercises description is sufficient to conduct all CAN bus exercises. During wiring the supervisors should take care of proper cable management. Otherwise, trouble-shooting will be extremely complicated. A best practice arrangement of devices and a proper wiring of a CAN bus exercise with one master microcontroller and two slave microcontrollers, all of them connected by CAN bus, is shown in Fig. 10.

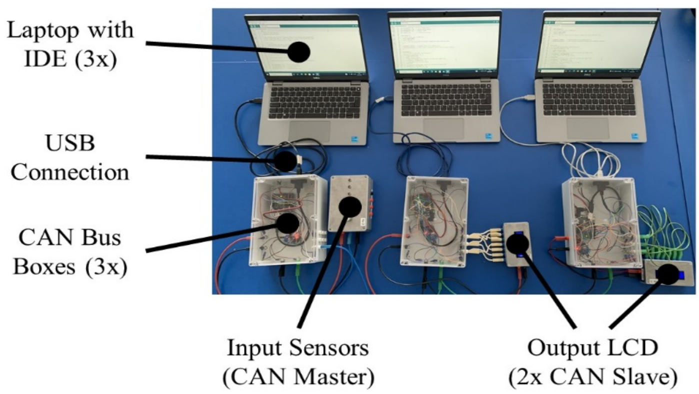

Fig. 10. CAN bus laboratory exercise with one master controller and two slave controllers

The future will indicate, especially with more and more groups passing the laboratory exercises, if further adjustments in CAN bus exercises, either in descriptions or in content, are necessary. For sure, the content of corresponding lectures has to be endorsed by CAN bus topics.

5. LABORATORY EXERCISES DESIGN FOR RC VEHICLE OPERATION

In this section the design procedure of RC vehicle exercises is described. Again, fundamental laboratory exercises were finalised. Even if they do not cover the ultimate requirements of autonomous driving so far, they are a first step towards them. The contents of these laboratory exercises are listed in Tab. 3.

Exercise	Content
1	Refill hydrogen storage stick with electrolyser, measure consumption of electricity, calculate efficiency of refilling process.
2	Operate RC vehicle just with driving battery on chassis dynamometer, measure energy consumption at steady-state condition, calculate driving resistance, compare results with real car values.
3	Operate RC vehicle in hybrid powertrain mode, simulate a driving cycle by braking action, observe and assess operation strategy by means of appropriate physical properties.

Table 3. Content of RC vehicle laboratory exercises

A first testing of laboratory exercise 1 has shown, the refilling process requires time periods between four and five hours. Hence, it is questionable whether this laboratory exercise could be conducted successfully. One reasonable possibility could be, that each group starts a refilling process at the end of their residence time in the laboratory. As the next group normally starts the following day, they could use the data from the previous group.

The composition of laboratory exercise 2 is shown in Fig. 11. First testing have shown, that feasible data could be measured. One deficit of the chassis dynamometer in actual layout is, that harsh braking is only possible for a period of about 8-12 seconds. Afterwards the braking is released automatically by the measurement controller unit. It is in accordance with manufacturer information a safety function to avoid overheating of the servo motor. Here some modification is necessary and will be carried out as soon as possible.

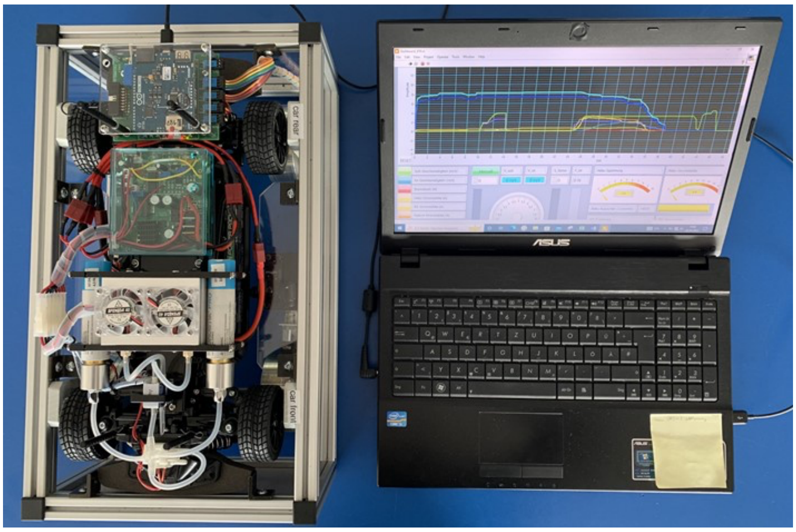

Fig. 11. Composition of RC vehicle laboratory exercise for measuring consumption data

Laboratory exercise 3 is carried out with the same composition as laboratory exercise 2. Vehicle velocity and necessary braking forces of the driving cycle used could either be supplied manually by scroll bars or could be imported as one sequence from especially prepared data files. The operation program displays operation data on the screen and accordingly enables saving of operation data to data files. Which data should be displayed respectively be saved could be selected via checkboxes. Possible operation data shown in the transient display area are

- velocity (target value and actual value),
- braking force,
- current (battery, fuel cell, hybrid),
- and voltage (battery, fuel cell, hybrid supply, electrical motor).

Additional information shown on the display are

- state of battery (actual voltage, actual current),
- remaining capacity of battery,
- and state of fuel cell (actual voltage, actual current).

A typical screen of the operating program is shown in Fig. 12. Furthermore, some minor information like measuring time, rate of reading/writing data, used communication port, etc. are visible.

Again, first testing has shown, that feasible data could be achieved. As visible in Fig. 12 observing and assessing of the hybrid operation strategy is possible. Periods of start-up of fuel cell, power supply from both energy storages, recharging of battery as well as exhausting of fuel cell due to low hydrogen pressure are clearly visible. However, testing with real or at least close to real driving cycles is shortened due to limitations in braking duration. Here, as mentioned above, some modification of the chassis dynamometer is obviously necessary.

Fig. 12. Showcase of display with typical measurement live data at hybrid powertrain action

Testing of RC vehicle exercises with groups of student are not conducted yet. This flaw will be eliminated within the next semester.

6. RESULTS AND DISCUSSION

Results and discussion have to be split into three sections. These are general microcontroller education, special CAN bus education and hybrid vehicle powertrain education by RC vehicle testing.

Analysis of main requirements of future automotive activities shows absolute need for knowledge in microcontroller-based systems for all mechanical engineers. The fundamental laboratory exercises referring to Tab. 1 fulfil this requirement as they give basic knowledge on microcontroller systems. Wiring is carried out robust. Laboratory instructions force proactive action of students with proceeding laboratory time. All laboratory exercises have clear reference to real automotive applications. Testing the laboratory exercises with a first group gave positive feedback. Hence, the authors will keep these laboratory exercises initially in the same way. However, the yearly feedback of student groups during the evaluation procedure has to be observed alertly. On the other hand, new requirements of automotive industry – like new sensors, different actors, new technologies in software engineering, etc. – has to be integrated as fast as possible.

Analysis mentioned above shows need for knowledge in connected microcontroller systems, too. This requirement is provided by laboratory exercises referring to Tab. 2. The authors have chosen CAN bus as connecting device, as low-cost hardware and software is available for the chosen microcontroller board. Furthermore, CAN bus is still number one in automotive bus systems. The laboratory exercises and the laboratory guidance are prepared the same way as those for microcontroller education. A first test with a volunteer student gave positive feedback. But, just one opinion is not representative. Here, testing with more students of different education level is necessary. Furthermore, trends in automotive bus systems should be observed continuously as there might be a change in direction to other bus systems of higher bandwidth. This is due to increasing data transfer rates among vehicles and their ambient on the way towards autonomous driving.

Laboratory exercises with the RC vehicle referring to Tab. 3 provide an insight into hybrid powertrains and their operation strategies. Due to export of operation data via data files further evaluation during wrap-up phase is feasible. Laboratory exercises are carried out much easier and with less risk compared to real chassis dynamometer testing. However, the model chassis dynamometer has need for massive improvements. Moreover, testing with groups of students is outstanding. From the authors point of view, to operate with hydrogen as probably number one energy source of the future is a priceless advantage for all mechanical engineering students, too.

Overall, the authors are pleased with the results of composition and first testing of all laboratory exercises. Nevertheless, there are still some improvements necessary.

7. CONCLUSION AND FUTURE WORK

Massive changes in automotive industry, like transformation of internal combustion engine driven powertrains to electrical and/or hybrid driven powertrains as well as more and more electronic components and/or systems, necessitate an adaption of mechanical engineering education. Obsolete contents of lectures and laboratories have to be replaced by up-to-date topics.

Referring to a new curriculum of mechanical engineering education lectures in automotive powertrains and automotive dynamics were updated. Especially the laboratory exercises were customised. For this purpose, new laboratory exercises in microcontroller education and CAN bus education were established. As platform Arduino based microcontrollers and CAN bus shields were purchased. Additionally, laboratory guidance was designed by considering didactical items like project-based learning and team work. All laboratory exercises show proper reference to automotive applications. This was done on purpose to make the students being interested in microcontroller education.

Regarding laboratory exercises of electric and/or hybrid powertrains, the decision to work with a model RC vehicle was made, as it is lower in cost and less dangerous. In principle laboratory exercises regarding driving resistance and energy consumption are possible. However, there is need for some optimisation work with the chassis dynamometer.

As not all laboratory exercises are tested with a statistical sufficient amount of people so far, the authors should be alerted to significant testimonies of yearly held evaluations.

Future work in this line of action should be focused on three main topics. First, eliminate flaws in chassis dynamometer, to make it work with close to real braking action, regardless of any time limitations. Second, observe continuously any change in direction of automotive technology like new bus systems, redesign of driver assistance systems, increasing fraction of autonomous driving options, changes in powertrain design, etc. If necessary, all these new technologies should be implemented into the laboratory exercises immediately. Third, take into account of increasing hydrogen activities in the laboratory exercises, as hydrogen seems to be one of the most probably energy sources in future. If so, all engineers should possess knowledge in hydrogen production, storage and consumption.

In this way, laboratory exercises and involved engineering education will always be up to date. Students should be well educated regarding actual requirements. This should result in highly motivated students, at least in our laboratories.

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