Human Interaction and Emerging Technologies (IHIET 2023), Vol. 111, 2023, 840–848
https://doi.org/10.54941/ahfe1004092

Modularized Platform for an Embedded Systems Case Study: Concept and Design

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ABSTRACT

Project-based learning is essential in bridging the gap between theoretical knowledge and practical application for electrical engineering students. To address this need, the Faculty of Electrical Engineering and Information Technologies (ETIT) at the Karlsruhe Institute of Technology (KIT) has developed a continuous mandatory workshop spanning the first four semesters. This workshop, executed alongside lectures and theoretical exercises, aims to provide students with a practical introduction to hardware-oriented programming and project management. In this context, the paper presents a newly-designed hardware platform for one part of the workshop, centered around a Tiva LaunchPad embedded on the control PCB of a modular remote-controlled vehicle. The platform leverages various capabilities of the Tiva Launchpad, enabling students to gain experience using GPIO, ADC, PWM, and UART peripherals. Working in groups of three, students develop individual hardware-related classes that contribute to group tasks, ensuring collaborative learning and project management experience. The hardware platform adopts a modular structure, effectively separating main functions and power levels through three printed circuit boards (PCBs): the control PCB, battery management PCB, and power management PCB. Additionally, a remote-control interface facilitates human-machine interaction. The software architecture follows a modular approach, employing object-oriented programming principles. Overall, the hardware platform provides first-year electrical engineering students with a practical and comprehensive introduction to hardware-oriented programming and project management. By integrating software and hardware components, the platform promotes a holistic understanding of systems engineering principles.

Keywords: Embedded systems case study, Modular hardware design, Systems engineering

INTRODUCTION

The practical application of learning contents is paramount in the education of electrical engineering students, not only due to the general disposition of putting theory into practice but potentially improving students' soft skills alike (Jollands et al., 2012). While the traditional lectures provide the students with the theoretical foundations, project-based learning offers the opportunity to bridge the gap between theory and practice. The faculty of Electrical Engineering and Information Technologies (ETIT) of the

Karlsruhe Institute of Technology (KIT) recognizes the need for objective-related laboratories across the bachelor's degree program and has therefore designed a continuous mandatory workshop (Beuth et al., 2013). The workshop spans the first four semesters and is attended in addition to lectures and theoretical exercises. For the duration of the workshop, the students are loaned several parts including but not limited to a DC motor, an ultrasonic sensor, LEDs, a Tiva LanchPad, and a breadboard.

At the Institut fuer Technik der Informationsverarbeitung (ITIV) the second-semester lecture *Informationstechnik I* is accompanied by the *Informationstechnik I – Praktikum (PIT)*, a project laboratory in which students work on an embedded systems programming task (Beuth et al. 2015). The goal is to provide the student with a practical introduction to hardware-oriented programming and project management. The workshop contains a case study for embedded systems programming in which students work in teams of three to solve a programming problem. The problem mimics a real-world scenario, where a customer hires an external programming team to bring their hardware platform into service (Tradowsky et al., 2015). The students are tasked to fulfill given customer requirements in a timeframe of seven weeks and afterward present their software product. Within this timeframe, the team has to understand the tasks, acquaint themselves with hardware-oriented programming (guided by the accompanying lecture), distribute the tasks, create a timetable and project plan, and program and test the different functions of the platform.

The hardware platform is the central component of the task. While in the past a two-wheeled self-balanced vehicle was used as a platform for multiple laboratories at the ITIV, a new platform was chosen. The new platform, same as the old, was not only to be used for the PIT but potentially be modified to be used for other ITIV labs as well, of which an overview can be found in (Beuth et al., 2015). Due to the large number of students in the PIT i.e., over 350 participants per year, individual testing of each student's code on the hardware platform was considered unfeasible. Thus, a means to abstract it with the hardware provided by the ETIT workshop was required, posing additional demands on the design of the platform.

The F1TENTH is one example of a platform used in laboratories across different universities. It is used for example by the University of Pennsylvania for a 15-week course on autonomous driving (O'Kelly et al., 2019) or by TU Dortmund for teaching cyber-physical systems design (Ueter et al., 2020). While the idea of using a vehicle as a platform for teaching is convincing, the ITIV requires a system capable of high modularization and the possibility to exchange the different PCBs to facilitate multiple workshops. Therefore, it was decided to develop an in-house solution for a remote-controlled vehicle. As a foundation, the Magni Silver™ robot base by Ubiquity Robots was chosen, as its design supports loads of up to 100kg. Only the original chassis, wheel and motor assembly, and sonar array were retained, while all other parts were replaced with a custom hardware platform.

While (Tradowsky et al., 2015) describe the old laboratory in its structure and evaluations, this paper focuses on the newly developed hardware platform. Therefore, the modular concept of the hardware platform is introduced and then the different components and their function on the PCBs are discussed in detail.

MODULAR HARDWARE PLATFORM

The platform needs to fulfill a multitude of demands. The primary requirements come from the case study itself and the ETIT workshop. Secondary requirements are set by the ITIV labs.

The case study is designed to pose programming tasks for students with little prior programming experience. They learn how to develop software for a microcontroller and work as a group in a structured way. On the one hand, simple, hardware-oriented classes, such as a PWM class, are to be included for each member of the team, as well as higher-level functions, that shall be implemented as a group. This results in the need for diverse, but simple usage of the microcontrollers capabilities on the platform. The ETIT workshops loans the required hardware for testing the code to the students for free. As it is fully sponsored, the costs of the parts required for testing should be low. High testability and low design complexity are additional requirements.

On the other hand, it should be designed for extensibility to fulfill the diverse needs of other laboratories. The design should prioritize high maintainability and adaptability to accommodate potential changes, for example, a new microcontroller being used in the student workshop. Additional requirements for specific design decisions are posed by the laboratory circuit design, in which three PCBs with similar functionalities are to be designed and tested by master's degree students.

To fulfill these requirements, a modular architecture was designed. Figure 1 depicts four main components divided by their functions: Battery Management, Power Management, Vehicle Control, and Remote Control. All of them have interactions with the main and secondary parts. The Battery Management facilitates functionality related to the platform's power supply i.e., battery charging, overcurrent protection, as well as an emergency shut-off. Power Management comprises the platform's power supply providing multiple voltage levels and its power electronics, interfacing the motors. Both of the PCBs can be reused by other labs with different vehicle controls. Vehicle Control generates the motor control signals based on control commands received from the Remote Control and environment information obtained from sensors. The Remote Control provides a user interface that allows the user to issue control commands and obtain information on the vehicle status. It communicates with the Vehicle Control using either a wireless connection or, as a fallback solution, the RS232 protocol. While all other components are fixed on the chassis and powered by the main battery, the remote control is powered using a power bank.

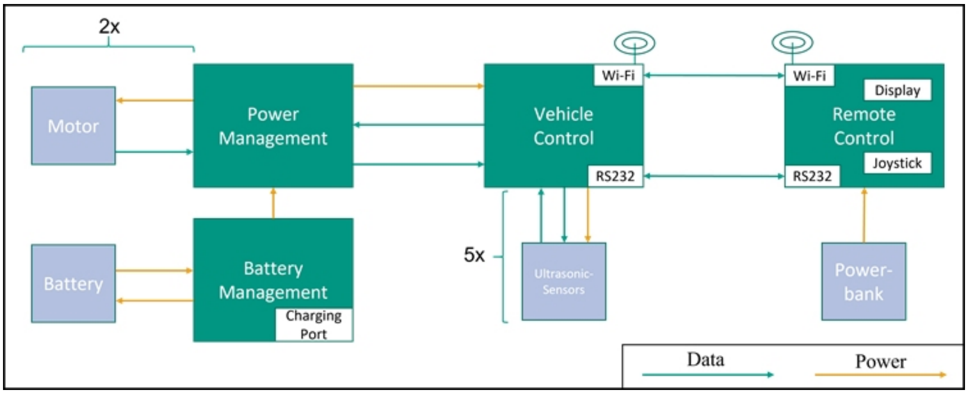

Figure 1: Modular hardware concept of the platform.

Battery Management PCB

The battery management PCB is designed to fulfill several battery-related functions. These are an overcurrent protection, a switchover between charging and operational mode, and an emergency stop mechanism. Overcurrent protection is realized using a main fuse. Regarding this fuse, the feasibility of resettable circuit breakers was considered. However, for the new platform, a 30A automotive fuse was deemed sufficient, as the cost of a resettable fuse was not justified.

For the emergency stop functionality, it was discovered that emergency switches capable of handling the full load current were either prohibitively expensive or unavailable. To address this, a combination of an automotive relay and a reed switch was implemented as a solution. The reed switch could be easily affixed at any desired location on the robot, while the associated magnet could be pulled away in any direction. The selected automotive relay is specified to interrupt up to 60A at 24V, which proved sufficient for shutting down the robot under the full rated load. Peak loads, reaching 80A-100A, are only expected for very short moments i.e., during startup. In these cases, a rapid decrease in current can be anticipated, thus causing the relay to disconnect. Otherwise, the fuse would trigger anyways, causing the robot to shut down. Therefore, this approach was deemed adequate given the anticipated scenarios.

To safeguard the connection between the battery management PCB and the power management PCB, multiple 5kW TVS diodes were employed, limiting the voltage during relay opening. To allow for switching connection between the battery and charging socket and the battery and power management PCB, respectively, a changeover relay was utilized. It ensures that the power management PCB is not connected to the battery while charging, and during operation (when the reed switch is closed), charging is not possible. This serves to protect the charger and prevent the hazard of leaving the charging cable in the port when driving. The charger plug is connected through an XLR socket, which is located on the PCB.

Power Management PCB

An overview of the power management PCB is shown in Figure 2. It receives motor control signals from the vehicle control PCB to drive the brushless DC motors used in the system. Additionally, it provides battery voltage and motor speed information to the vehicle control PCB, allowing for more advanced vehicle control and monitoring.

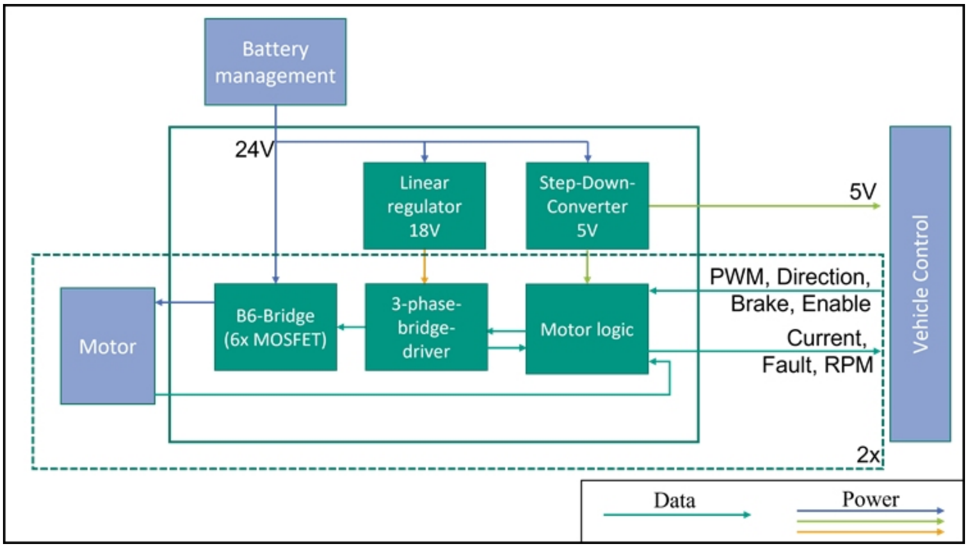

Figure 2: Overview of the power management PCB.

The power management PCB's main functionalities are controlling the motors through a three-phase bridge configuration and supplying different voltage levels required by the different system components. Receiving signals from the control, the power management PCB generates gate signals for the driver based on the current motor position, which is obtained from the motor's hall sensors. Moreover, the PCB incorporates battery voltage and current measurement capabilities.

The power management PCB is designed to be compatible with 24V lead-acid batteries and can independently control two motors. The motors used in the system are rated at 250W, and although they have a nominal current of approximately 11A, they experience higher currents during start-up. Therefore, the power management PCB was designed to handle short-term currents of up to 40A, ensuring safe and effective heat dissipation.

The motor logic serves as a connection between the Hall sensors' feedback, control specifications, logic signals for the gate driver, and possible error signals. Each motor requires its own logic module.

Fully integrated drivers for all six bridge gates are used. They offer voltage and current monitoring features, allowing for easy integration of overcurrent protection. The PCB includes protection diodes for gate voltage spikes, addressing previous issues.

In the selection of components for the power management PCB, particular attention was given to the power stage MOSFETs. MOSFETs with a rated voltage of 75V and a rated current of 76A were chosen, as they exceed the requirements and possess suitable switching times for efficient operation. To ensure the required cooling, one heat sink per three-phase bridge configuration is used. Each heat sink is designed to dissipate the power losses generated by six MOSFETs.

The power management PCB requires four voltages: 24V for the motors, 15-18V for the gate drivers, 5V for the Hall sensors and EEPROMs, and 1.8V for current monitoring. Due to the low current requirements and the complexity of the power management PCB, linear regulators were initially chosen for the auxiliary voltages. For 5V the change to a step-down converter was made, as it supplies the vehicle control PCB as well. A transistor regulator is used to generate the 1.8V supply. The heat sinks for the MOSFETs were designed with extra space, allowing them to be used for the voltage regulators as well. Four wires (two GND, two 24V) are used for battery connection to meet the current rating. This approach allows for smaller wire diameters.

The power management PCB has undergone extensive testing to validate its design and functionality. Various tests were conducted, including motor control tests, battery voltage and current measurement tests, and heat dissipation tests. The PCB demonstrated motor control, accurate measurement of battery parameters, and efficient heat dissipation, meeting the design objectives and ensuring reliable operation of the brushless DC motor system.

Vehicle Control PCB

The vehicle control PCB, as shown in Figure 3, is connected to the power management PCB and the remote control PCB. The connection to the power management PCB is used to supply the vehicle control PCB with power, control the motors, and get information about possible faults, the motor speed, and motor currents. The connection to the remote control enables the user to view the current battery charge and speed while controlling the robot. Five ultrasonic sensors are connected to detect objects in front of the vehicle.

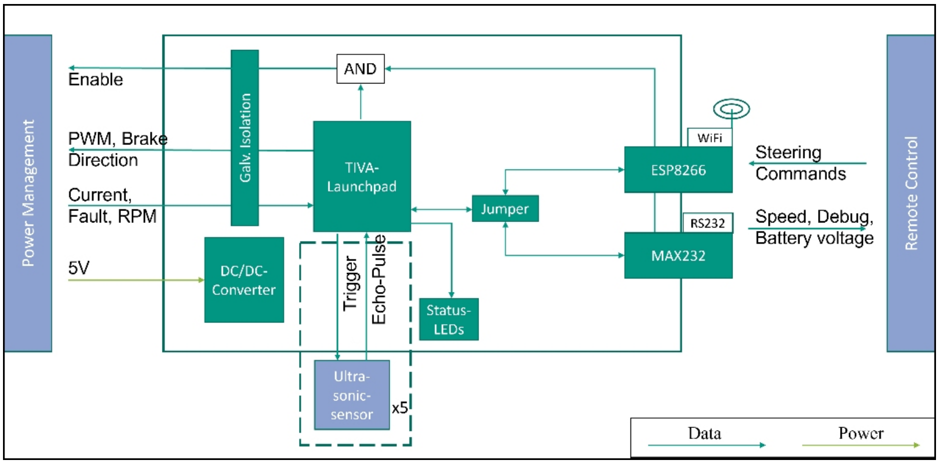

Figure 3: Overview of the vehicle control PCB.

The main function of the vehicle control PCB is to arbitrate the different inputs and control the vehicle. It acts as an interface between the power management PCB and the remote control PCB, establishing essential connections that enable seamless communication and control of the vehicle's functionalities. Additional functionalities, such as other sensors or higher computing power, could be achieved by replacing this PCB with a different version.

The center of the design is an EK-TM4C123GXL LaunchPad (TIVA LaunchPad) by TI. This enables students to use their own LaunchPad for deploying code to the robot by flashing it before putting it on the robot. A separate benefit of this is reduced design effort.

The LaunchPad receives steering commands by the remote control either via a Wi-Fi connection or (as a backup) an RS232 connection. The used connection can be selected through a jumper, connecting either a MAX232 or ESP8266 to the TIVA LaunchPad. As information for the users, the measured speed, selected debug values, and the battery voltage are sent to the remote control. The messages are sent and received over UART.

As a requirement from a different workshop, all data connections to the power management PCB are galvanically isolated using optoisolators. For the power supply, a DC/DC-Converter with isolation is used. As a safety measure a logic circuit is used to enable the motors only if the TIVA LaunchPad sends an enable signal and the connection to the remote control is stable. The connections for the motor control exist twice, once for each motor.

Another safety measure is the ultrasonic-sensor array. Five sensors are mounted in the front of the vehicle to avoid collisions. This setup is already provided in the original Magni Silver™ configuration. To control the sensors a trigger pulse is sent and the width of the echo-pulse is measured.

The vehicle control PCB serves as a crucial intermediary between the power management PCB and the remote control PCB. It facilitates seamless communication, and efficient control of the vehicle's functionalities, and provides valuable feedback to the user.

Remote Control PCB

While the remote control PCB is not mounted on the robot itself, it serves as the front end for the user and receives inputs through four buttons and a joystick. The received inputs are used to navigate a user interface and steer the robot.

As shown in Figure 4, a battery in the form of a commercially available 5000mAh power bank supplies the system. The remote control PCB can be switched on and off through a lever switch. A linear voltage regulator on the TIVA LaunchPad is used to create a 3.3V level for the peripherals on the PCB.

On the LCD Display information for the user is shown. To switch the displayed information, for example, to a debugging view, four pushbuttons in a cross formation are connected to GPIO-Pins of the TIVA LaunchPad. The joystick contains two potentiometers, one per axis. This allows for an exact control of the steering, by reading the output through the internal ADC of the TIVA LaunchPad. An additional GPIO Pin is connected to the Joystick as it can be pressed as well.

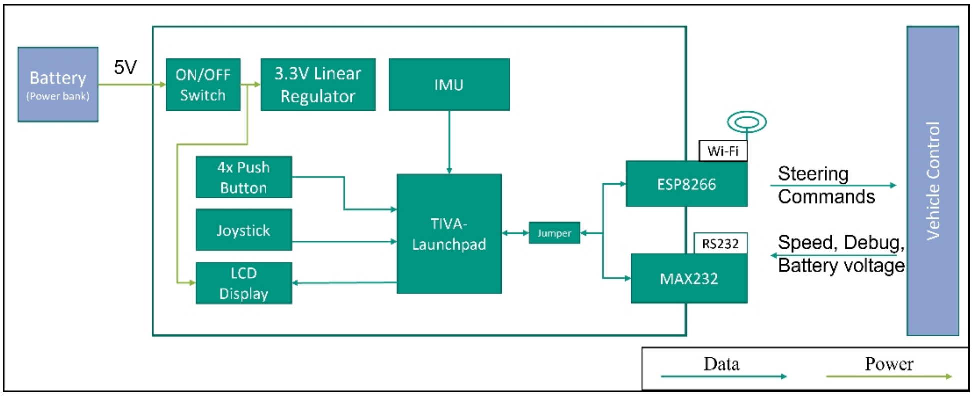

Figure 4: Overview of the remote control PCB.

As a secondary means of control, an inertial measurement unit (IMU) can be mounted to the PCB. The idea is to lean the remote control to steer the robot. This possibility is however not used for the workshop, as it does not seem necessary. The IMU is connected via I2C to the TIVA LaunchPad.

Same as for the vehicle control PCB, two separate possibilities for connection are implemented. The primary data exchange is over a Wi-Fi connection through an ESP8266, while an RS232 connecter serves as the backup. The selection of the channel again is made by changing a jumper on the PCB.

Deployed Hardware Platform

To show the hardware platform in its finished version, Figure 5, gives a bird's eye view of all the PCB. On the upper left is the battery management PCB (1). The power management is located in the center, identifiable with its heatsinks to facilitate the losses in the MOSFETs and voltage converters. The vehicle control PCB (3), with the prominent placement of the TIVA LaunchPad in red, is on the lower left. Finally, the remote control PCB (4) shows the User Interface in the LCD-Display. The TIVA Launchpad on the remote control is mounted on the backside, and therefore not visible.

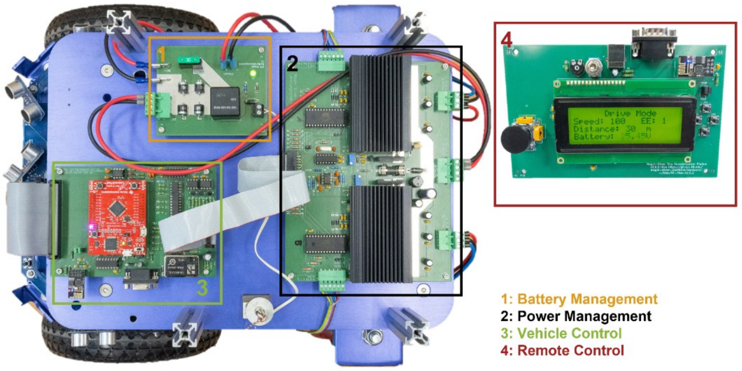

Figure 5: The deployed hardware platform.

CONCLUSION

Project-based learning is an important aspect of teaching engineering students in early semesters. It helps to keep them engaged with the study program and teaches important soft skills while cementing the contents from lectures and exercise classes. With the new hardware platform introduced in this paper, students will be able to learn about hardware-oriented programming. The design was chosen to be as modular and maintainable as possible while allowing for future expansions, changes, and upgrades. Overall, the hardware platform provides first-year electrical engineering students with a practical and comprehensive introduction to hardware-oriented programming and project management. By integrating software and hardware components, the platform promotes a holistic understanding of systems engineering principles.

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