ABSTRACT

Formula Student vehicles are becoming increasingly complex, especially with the current shift from internal combustion engines toward electric powertrains. The interaction between software and hardware is complex and imposes additional challenges for systems integration. This paper provides a structured introduction to the OBR22 Oxford Brookes Racing Formula Student electric vehicle. From a system architecture perspective, the four-wheel drive in-hub motors topology is described. Diagrams of the hardware components, the architecture of the high voltage and communication systems are presented. This paper also demonstrates the model-based development process, including an overview of the model-in-the-loop (MiL) and hardware-in-the-loop (HiL) control design phases.

Keywords  Model-based Systems Engineering · V-model · MiL · HiL · Vehicle controls
To address project complexity, a methodology should consider requirements and interactions between subsystems early in the system design. A relevant approach is model-based systems engineering (MBSE). It takes the systems engineering premises - defining what a system must do, how well a system must work, and how system functions are tested [Buede 2009], using modelling and simulation as the means of information exchange instead of a document-centric approach [Capasso et al., 2017]. The primary focus of MBSE is to ensure integration and understanding of a system from multiple perspectives [Gräßler et al., 2021]. This process is guided by a V-model framework that is represented by the design process from requirements on the left to hardware integration. The V-model approach is further explored in section 5.

In the context of a Formula Student team, a V-model development process was demonstrated by [Schumacher et al., 2021] in the design of a four-wheel drive (4WD) electric drivetrain, from concept to system realization. In this MBSE approach, an executable platform was created using AVL eSUITE™ software to run multi-domain simulations, which enabled the design and integration of components along the entire design cycle. From a mechanical design viewpoint, the concept of the in-hub motor was also addressed by [Kucinski et al., 2017] from top-level requirements to hardware validation. However, the interfaces between software and hardware in the development process of a Formula Student electric vehicle are still not clear from the literature. This paper address this gap by providing an overview of the system architecture and development process of the OBR22 electric powertrain, the first electric vehicle from the Oxford Brookes Racing team (Figure 1).

Figure 1: OBR22 Formula Student electric vehicle.

In the following sections, the OBR22 4WD system is presented with increasing levels of detail from different points of view. Firstly, software and hardware development aspects are distinguished in Section 2, followed by a brief description of the battery pack, motors and inverters. Sections 3 and 4 present the high voltage and communication systems architecture. Finally, section 5 gives an overview of the MBSE methodology, and explores the development process from a model-in-the-loop (MIL) and hardware-in-the-loop (HIL) perspectives. Section 6 concludes this paper.

2 System Overview

2.1 Vehicle Control Unit (VCU): the interface between software and hardware

The majority of the Formula Student vehicles running internal combustion engines use off the shelf programmable electronic control units (ECU) for engine management. Although it is possible to develop new advanced algorithms, usually programmable engine ECUs are only required to be configured and calibrated to a particular engine design. For electric vehicles however, despite of having fewer components compared to an engine vehicle, the number of different vehicle system typologies requires customized software control solutions to be closely related to the system hardware [Schumacher et al., 2021, Badal, 2019].
In a 4WD in-hub architecture, the management of the torque request for each motor is crucial for achieving a functioning system. This alone requires development of specialized vehicle control algorithms as an inherent part of the tractive system. It is needed for performance features and also for the safety limits imposed by competition rules [Institution of Mechanical Engineers - IMechE, 2022]. Therefore, the development of control algorithms for a 4WD in-hub Formula Student vehicle is not a choice, it is very much part of the system, in the same way as the battery cells are or any other hardware component.

Figure 2 illustrates this concept, where software and hardware are highlighted as two major areas of the OBR22 powertrain development. From a simplified standpoint, the algorithm developed in Simulink [The MathWorks Inc., 2022] controls the energy flows within the tractive system: it provides limits for power output and manages the torque requested by the driver across all four wheels based on vehicle sensor readings.

Figure 2: Hardware and software overview of the electric vehicle. Software is developed in Simulink and uploaded into the VCU, which is the interface between software and hardware. The VCU takes inputs from sensors and sends a torque request to the inverters. The accumulator is the high voltage supply of the system.

The vehicle control unit (VCU) is a supervisory controller that provides the top level control between all the vehicle subsystems. Where each vehicle subsystem is typically controlled by a local electronic control unit (ECU). A strict differentiation between VCU and ECU devices varies among manufactures, however in general terms a VCU due to its flexible nature is typically a fully programmable real-time computer.

The VCU in the OBR22 vehicle is an ETAS ES910 rapid prototyping module, a real-time computer with significantly higher computing performance than an ECU [ETAS GmbH, 2018]. Typically VCUs provide an integration with a platform such as MATLAB/Simulink to enable the development of signal flows and state machines, and this is how the OBR vehicle controls algorithms are developed, with the help of INTECRIO software [ETAS GmbH, 2022a] and its INTECRIO-RLINK Simulink Blockset [ETAS GmbH, 2022b].

2.2 Motors and inverters

From a hardware standpoint, the main components of an electric powertrain are: motors, inverters, accumulator and gearbox. OBR22 uses off-the-shelf motors and inverters provided by AMK in the package "Racing Kit 4 wheel drive Formula Student Electric". A summary of the motor AMK DD5-14-10-POW technical data is given in Table 1, where the rated operating condition relates to continuous output with controlled heat dissipation and the maximum operation relates to output over a short time that avoids overheating the motor windings. The AMK inverters limit the maximum operation condition to a duration of 1.24 seconds.

The AMK motor is a permanent-magnet synchronous motor (PMSM). Compared to an induction motor, a PMSM design with an equivalent power rating have increased power density, greater torque-to-inertia ratio, are more efficient and easier to cool even though PMSM motors are more sensitive to higher operating temperatures [Husain, 2021].
Table 1: Summary of the motor AMK DD5-14-10-POW technical data [AMK Arnold Muller GmbH & Co. KG 2020].

| Parameter | Rated Value | Maximum Value |
|-----------|-------------|---------------|
| Power     | 12.3 kW     | 35 kW         |
| Torque    | 9.8 N.m     | 21 N.m        |
| Current   | 41 A        | 105 A         |
| Speed     | 12000 rpm   | 20000 rpm     |

1 for a voltage supply of 600 VDC
* root mean squared current draw

Although the peak power of each motor is 35kW (as shown in Table 1), the total maximum power of the powertrain is limited to 80kW by the competition rules [Institution of Mechanical Engineers - IMechE 2022]. In addition, the maximum power is dependent on the supply voltage from the accumulator, which decreases as the state of charge depletes. This effect was further explored in [Barham 2017], where the effect of various supply voltages on power and torque were analysed.

The AMK motor operates with alternate current (AC), whereas the battery pack supplies direct current (DC). The primary function of the inverters is to convert the battery DC into motor AC. This is accomplished by using high frequency switches to activate the current flow through the windings of the motors in a synchronous manner. Each inverter uses six insulated-gate bipolar transistors (IGBTs). Compared to alternatives such as silicon carbide (SiC) MOSFETs, these high frequency switches are considered to be the main disadvantage of the AMK package due to its size, weight and its lower efficiency [Galbraith 2019]. For more information on how the inverters work the reader is referred to [Larminie and Lowry 2012].

Figure 3 summarizes the energy control flow between the VCU, motors and inverters. This starts with driver’s input (accelerator pedal position, brake pressure and steering angle) and the vehicle sensor readings, from which the VCU algorithms evaluate the vehicle states and imposes limits for maximum performance (e.g. torque vectoring, energy consumption). Then, the VCU sends to the inverters an optimized torque request for each wheel, where another check of safety is performed by the inverters to make sure the temperatures of the motors and IGBTs are within safe limits. Finally, the current is controlled by the inverters and switched through its IGBTs to provide AC current to the motors where electrical energy is converted into mechanical energy.

Figure 3: Energy flow of torque request. Inputs from the driver are translated by sensors and sent to the VCU where an optimized torque request is calculated based on vehicle sensors. This torque request is sent to the inverters where it is checked against internal limitations and DC current is converted into AC current to power the motors.

2.3 Accumulator

There is a great variety of lithium-ion battery cells in the market. From cell chemistry to the form factor, each cell has its unique characteristics and trade offs. There are three common types of form factors: cylindrical, prismatic and pouch
cells. Both cylindrical and prismatic are contained in hard cases, whereas pouch cells are encased in soft pouches. Due to the dynamic pressure during charge and discharge of lithium-ion battery cells, pouch cells require a constant external pressure to increase mechanical stability. This pressure is directly related to performance aspects (for example, aging and capacity fade), and safety aspects such as dynamic instability due to gas formation, a problem known as swelling (Zhou et al., 2020). Despite these design requirements, pouch cells have higher power density \( \text{W/m}^3 \) and energy density \( \text{Wh/m}^3 \) than cylindrical and prismatic cells. Additional, they can be packed more closely, saving space and reducing mass.

Table 2: Overview of the Melasta SLPBA442124 cell [Shenzhen Melasta Battery Co., Ltd, 2019].

| Parameter                     | Discharge | Charge |
|-------------------------------|-----------|--------|
| Maximum continuous current    | 110 A     | 11 A   |
| Peak Current (\( \leq 3s \))  | 137.5 A   | 16.5 A |
| Voltage                       | 3 V       | 4.2 V  |
| Operating temperature         | -20 ~ 60 °C | 10 ~ 45 °C |
| Nominal Capacity              | 5.5 Ah    |        |
| Weight                        | 116 g     |        |

The cell chemistry is beyond the scope of this paper, but the technical data of OBR22 Lithium Cobalt Oxide (LCO) pouch cells is presented in Table 2. The maximum discharge capacity that a cell can safely deliver is described as the C-rate, computed as the maximum continuous current [A] divided by its nominal capacity [Ah]. The Melasta SLPBA442124 has a C-rate of 20, which in practice means the cell could be discharged entirely in 3 minutes. For further information about battery terminology the reader is referred to [Team, 2008].

Besides the battery cell, the battery pack configuration is an important aspect of the accumulator design. A combination of series and parallel arrangement is normally used to meet voltage and current requirements. According to the
competition rules, any connection between two electrical components of the tractive system must not exceed the voltage of 600V (EV4.1.1 [Institution of Mechanical Engineers - IMechE, 2022]). Within this constraint, higher voltages are preferred because power losses ($P_{\text{loss}} [W]$), computed as $RI^2$, are proportional to the square of the current $I [A]$ and proportional to the electrical resistance of the system $R [\Omega]$. Therefore, for the same amount of power output $P [W]$, higher voltages require lower current draw because $P = VI$, and consequently less power loss, smaller wire gauges and ultimately lighter components. The OBR22 accumulator (Figure 4) operates with 600V at full state of charge and contains 288 cells arranged in a 2P144S configuration (two cells connected in parallel for each of the 144 connection in series).

To comply with the rule EV 5.3.2 [Institution of Mechanical Engineers - IMechE, 2022], which limits the accumulator segments to a maximum of 6MJ and 120V DC, the 2P144S configuration is further divided into six segments wired in series, each in a 2P24S configuration (48 cells configured with two cells connected in parallel and 24 cells in series). The accumulator has a nominal energy capacity of 5.8kWh, computed using Equation 1 [Plett, 2015],

$$Q_{\text{pack,nom}} = N_{\text{cells}} \cdot V_{\text{nom}} \cdot Q_{\text{cell,nom}}$$

where $N_{\text{cells}}$ is the total number of cells in the accumulator, $V_{\text{nom}} [V]$ is the nominal cell voltage and $Q_{\text{cell,nom}} [Ah]$ is the nominal cell charge capacity.

3 High Voltage system architecture

The OBR22 high voltage system comprises motors, accumulator, the tractive system – defined by the rules as every part electrically connected to the motors and the accumulator, and several safety features connected to a centralized shutdown circuit. Figure 5 gives an overview of the high voltage system and how the development areas are structured within OBR team.

![Figure 5: OBR22 high voltage system architecture.](image)

The Tractive System Accumulator Container (TSAC) is surrounded by strict rules and encloses all unswitched high voltage components. Its development includes notable integration of many areas of development such as composites – for mechanical design and manufacturing of the casing, tractive system, low voltage electronics and electrical integration. The Battery Management System (BMS) within the TSAC is responsible for estimating the battery states (for example the state of charge and state of health). The monitoring of cell voltages and temperatures is performed in OBR22 by an auxiliary Temperature Monitoring Device (TMD). The BMS is connected to the shutdown circuit and can open the two
Accumulator Isolation Relays (AIR) in case any safety limit is exceeded. Opening the AIRs completely shuts the high voltage supply from the TSAC to the vehicle.

The high voltage system also includes printed circuit boards (PCBs) specifically designed to ensure overall system compliance: The Tractive System Active Light (TSAL) PCB indicates the status of the system and the Brake System Plausibility Device (BSPD) PCB checks if power is being applied to the motors whilst the vehicle is under hard braking, if true it opens the shutdown circuit through the shutdown PCB. This is done by measuring the HV current via a Hall Effect Current Sensor (HECS) and a brake pressure sensor. The precharge PCB protects the inverter capacitors from inrush current from the accumulator when the AIRs are closed, whereas the discharge PCB removes potential dangerous residual high voltage stored in the capacitors after the AIRs are opened. Finally, the last component depicted in the diagram, the High Voltage Disconnect (HVD), is a removable connection of the accumulator negative pole. By rules, the HVD must be manually removable by an untrained person without the need of tools.

4 Communication architecture

The backbone of OBR communication is the Controller Area Network (CAN). Channels from sensors and devices are integrated by four main CAN bus lines at vehicle level (Figure 6).

Figure 6: OBR22 vehicle communication system architecture.

CAN 1 and 2 connect the inverter controllers with the vehicle control algorithms to the VCU. Motor speed, torque, temperature are sent to the inverters by encoders mounted to each motor, which are sent via CAN by the inverters to the VCU and to the data logger where they are recorded. The vehicle sensors are integrated in CAN 3, they are either powered by the Power Distribution Module (PDM) or directly connected to the data logger. The PDM is a power distribution unit that replaces conventional relays and fuses, and the data logger is integrated into the Bosch DDU7 dashboard display. Finally, the accumulator has its own CAN 4 with several configurable channels, including voltages and temperatures at cell and battery pack level.

4.1 Configuration software

Figure 7 illustrates the software used with each device and the type of connection with PC (USB or Ethernet cable). This software allows the configuration of devices, and access to data on CAN buses. CAN signals can also be accessed directly via USB connection with the help of a CAN interface [Vector Informatik GmbH, 2022] and the Vector CANoe...
software [Vector Informatik GmbH, 2021] (right side of the diagram). This tool is tailored to deal with CAN buses and enables both reading and sending signals to devices.

Figure 7: OBR22 user-vehicle communication system architecture.

The VCU is accessed throughout ETAS INCA Software [ETAS GmbH, 2020] via Ethernet connection and it is the means of loading the vehicle controls algorithms into the VCU. The inverters are accessed via Ethernet cable using the AMK AIPEX Pro software [AMK Arnold Muller GmbH & Co. KG, 2019], each inverter has its own Ethernet port and therefore might be connected one at a time in a PC. The PDM module is accessed through Ethernet and is configured with the help of the Bosch PBX Suite software. Finally, the BMS needs a CAN adapter to be accessed through the Orion BMS software in which the accumulator topology and the CAN 4 channels are configured.

These controller devices are extensively accessed during design phases, whereas during vehicle testing phase CAN channels are centralized in the data logger software Bosch WinDarab [Bosch Motorsport, 2021]. This is a data acquisition and analysis tool capable of displaying signals in various formats including plots over time or distance, helpful to identify trends and issues because the correlation to other physical, temporal and location measures can be inferred all in a single tool (e.g. temperatures, bumps in the tarmac, high acceleration corners).

5 Model-based approach for vehicle controls development

Because the competition event has a predefined timeline, project planning quickly becomes a major factor of success. Testing time on track is valuable and sensible project planning is needed but challenging to achieve considering the high turnover rate of team members. Therefore, the development process must allow new engineers to quickly understand the working principles of the system, how design phases are structured and essentially what needs to be accomplished in each phase of the project.

New designs naturally involve high levels of uncertainty, however most of the time systems are not designed from scratch, but rather are an evolution from a previous design. The project plan then becomes a task list of what needs changing for each design iteration and what is already known to work well is left alone. The ultimate goal is to achieve continuous development where there is a fast iteration from one stable design to the next stable design.

Figure 8 gives an overview of the OBR model-based development process for vehicle controls and illustrates the various software tools used in each phase of the project. On the left side of the diagram, the objective is to propagate design requirements from a system to a component level in a top-down approach. On the right side, the objective is to validate the system performance by increasing integration of components in a bottom-up approach [Capasso et al., 2017]. To further explore the V-model, an overview of each phase of the process is given, starting from the requirements on the top-left of the diagram.
5.1 Requirements and system architecture

The system design is constrained by technical requirements and competition regulations. The documentation of these requirements is the first phase of the design process, it helps understanding the reasoning behind design decisions and the critical aspects new developments that should be taken into account. In fact, it is not effective to start developing new functionalities if the existing system is not reasonably understood. There is a learning curve, that takes a short time or long time depending on the complexity of the system, however, experience shows that comprehending the top-level working principles of the system and the relationship between components makes the lower level technical details easier to follow as consequence. The second stage of the process, system architecture, addresses this gap (that is figures 5, 6 and 7) by representing the system from different perspectives, to provide a conceptual map of the system.

5.2 Vehicle controls prototype (MiL) and code generation

The development of vehicle control algorithms happens in the third phase: model-in-the-loop. Vehicle controls can be thought as a black box input/output system which takes sensors inputs (steering angle, accelerator and brake pedal positions, for example) and transforms it into a torque request to each motor. These algorithms are developed in Simulink and tested in a virtual environment before they are implemented in the real vehicle. This approach has several advantages, engineers can conduct tests at critical conditions that are not possible or difficult to be safely replicated in real life. For example, the torque limitation to prevent battery cells of exceeding critical temperatures can be tested multiple times to find the optimum strategy to increase performance while keeping the system safe.

Once the vehicle control algorithms are modelled and tested in Simulink, they need to be uploaded into the VCU. However, to make best use of the computational power of the VCU, Simulink models are not deployed directly into it. Instead, efficient code is generated with the help of a proprietary Simulink Blockset ETAS INTECRIOR R-LINK [ETAS GmbH, 2022b]. This creates an executable file (.a2l) which is then uploaded via an ethernet connection using the ETAS INCA software. Once this process is completed (a couple of minutes), the VCU is ready to run.

5.3 Integration (HiL) and system calibration

Ideally, the virtual vehicle represents the real vehicle very closely, however, vehicle models are only a representation of the real system and deviations from reality are an intrinsic part of the process. During this phase the actual vehicle is still not finished and the physical properties that cannot be measured need to be estimated. The integration of real hardware attempts to fill the gaps between the virtual and real environment using a variety of bench testing.

A detailed description of such tests are beyond the scope of this paper and largely depends on the specifics of the project, which changes from year to year. Nevertheless, in general terms the integration begins with the VCU and, one step at time, sensors are included in the system and monitored in a PC with the help of the Vector CANoe software, capable of
displaying information from any of the four CAN buses. Next, the motors and inverters are integrated and monitored using the AMK AIPEX Pro software. At this stage the inverters are powered by a high voltage power supply which is later substituted by the accumulator and monitored with the Orion BMS software.

The integration phase aims first to check basic functionalities such as CAN communication, and to test if the physical behaviours of the components are as expected. At the same time, this creates clear milestones that can be restored if problems occur in the following phases of integration. This is the reason for progressively incorporating hardware components instead of connecting the entire system all at once. It is easier to find and prove out each localised subsystem at time. This process continues until the entire system is at its full functioning state. Finally, there is a transition from bench testing to the real vehicle testing: the system calibration phase. This stage deals with the final details of hardware implementation and aims to fine tune the vehicle control algorithms. In reality, the V-model is not a linear process tasks cycling back and forth with iterations between the integration and calibration phases, and with the vehicle controls prototype. This iterative approach also feeds back to the requirements that are needed to achieve a better and safer design.

6 Concluding remarks

The system architecture of a Formula Student vehicle with 4WD in-hub motors was introduced. First, the interface between hardware and software was demonstrated. Major components of the electric system such as the accumulator, inverters and motors were described and the interfaces with other devices of the high voltage system were illustrated in the format of block diagrams. In a similar manner, the communication architecture was presented from a vehicle perspective and a user perspective. Software tools supporting engineers to access the electronic devices and data on the CAN buses clarified when and how each tool is used along project phases. Finally, the OBR vehicle controls V-model development process was presented. This methodology was based on the current automotive industry approach but simplified to promote smooth integration of young engineers.

Designing a Formula Student electric vehicle faces similar challenges to the challenges that the automotive industry faces in the race towards electric mobility. It stretches the limits of knowledge, and the efficient usage of resources and promotes intense teamwork. The collaboration with companies is beneficial for both the students who can make better designs based on engineering approaches at a professional level, and for the companies who can hire better-prepared students with real-world experience.

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