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DESIGNING AND IMPLEMENTING THE CONTROL SYSTEM SOFTWARE FOR A HYBRID CITY BUS PROTOTYPE

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TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta
Sähkötekniikan koulutusohjelma

Jani Alho

Prototyyppihybridilinja-auton ohjausjärjestelmän ohjelmallinen suunnittelu ja toteutus

2016

Diplomityö.
76 sivua, 18 kuvaa, 2 taulukkoa, 3 liitettä.

Tarkastajat: Professori, TkT Olli Pyrhönen
Tutkijaopettaja, TkT Tuomo Lindh

Ohjaaja: Tutkijaopettaja, TkT Tuomo Lindh

Hakusanat: autotekniikka, linja-autot, hybridiautot, ohjelmoitavat logiikat, testaus, riskinhallinta, turvallisuus

Keywords: automotive engineering, buses, hybrid electric vehicles, programmable logic controllers, testing, risk management, safety

Nykyiset ympäristösuuntaukset vauhdittavat ekologisempien ja vähemmän saastuttavien ajoneuvojen kehittämistä. Ajoneuvojen ja lyhyillä työsykleillä toimivien työkoneiden hybridisointi on osoittautunut tehokkaaksi tavaksi vähentää polttoaineenkulutusta ja päästöjä. Kaupallisessa mielessä uudet teknologiat ottavat vielä ensiaskeleitaan valmistajien kehittäessä ja kokeillessa erilaisia teknisiä ratkaisuja.

Uudenlaisen tekniikan jälkiasentaminen vanhempiin ajoneuvoihin saattaisi jatkaa niiden käyttöikää. Lappeenrannan teknillinen yliopisto on rakentanut vanhemmasta kaupunkilinja-autosta sarja-rinnakkaishybridin. Meneillään oleva tutkimus pyrkii selvittämään, voitaisiinko tämänkaltainen jälkiasennus tehdä kaupallisesti kannattavaksi.

Tämän työn tarkoituksena oli kehittää hybridin ohjausjärjestelmää varten ohjelmisto, joka on riittävän turvallinen julkiseen käyttöön ja pystyy tuottamaan mittaustietoa tutkimusta varten. Tämä työ kuvaa kehitysprojektin ydin- ja tukiprosessit sekä esittelee niiden eri vaiheisiin liittyviä menetelmiä, muun muassa riskienhallintaa ja testausta. Rajallisista henkilöresursseista riippumatta projekti kykeni osoittamaan, että pienemmissäkin prototyyppiprojekteissa voidaan saavuttaa tyydyttäviä tuloksia soveltamalla mukautettuja teollisuusstandardien mukaisia menetelmiä. Työn johtopäätös on, että aktiivinen projektinhallinta ja järjestelmälliset suunnittelumenetelmät ovat avain monitahoisen projektin onnistumiseen.

ABSTRACT

Lappeenranta University of Technology
Faculty of Technology
Degree Programme in Electrical Engineering

Jani Alho

Designing and implementing the control system software for a hybrid city bus prototype

2016

Master's Thesis.
76 pages, 18 pictures, 2 tables, 3 appendices.

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Current environmental trends are pushing the development of more ecological and less polluting vehicles. Hybridization of vehicles and heavy-duty machinery with short duty cycles has already proved to be an effective way to cut down fuel consumption and emissions. The new technologies are still taking their first steps commercially, and the manufacturers are developing and testing different solutions.

Retrofitting new technologies into older commercial vehicles could be one solution to extend their lifespan. Lappeenranta University of Technology has equipped an older city bus with equipment capable of series-parallel hybrid operation. On-going research is trying to establish whether this kind of retrofitting could be made commercially viable.

The aim of this work was to develop hybrid control system software ensuring safe public operation and capable of providing measurement data for research purposes. This work essentially describes the core management process and its support processes. It explains some basic methodology for each phase of this engineering project, covering for example risk management and testing. Despite limited human resources, the project demonstrates that industrial standards methods can successfully be scaled down, used in a small-size prototype project and provide satisfactory results. The work concludes that active project management and structured design methods are key factors in successfully completing a project with such complexity.

ACKNOWLEDGEMENTS

This master's thesis was carried out at Lappeenranta University of Technology (LUT) in the Department of Electric Engineering as a part of a hybrid city bus project named CAMBUS.

I would like to thank Professors Olli and Juha Pyrhönen for the opportunity to participate in the project. In addition, I want to express my profound gratefulness to Associate professor Tuomo Lindh for the supervision of this work, and for all the support and guidance throughout. I would also like to thank all the CAMBUS project associates and colleagues for their ideas and collaboration. It sure has been an interesting and educational journey. During the project, I also had the chance to meet some of the most amazing people working in the automotive sector. Especially Juhani Tikkanen deserves my humble gratitude. Thank you for all your ideas and support.

My sincerest gratitude goes to my parents for all their support during these years; and finally, I'd like to send warm thanks to all my friends. We have spent countless hours talking and reasoning, always learning something new together. Never get weary.

Jani Alho
November 2016
Lappeenranta, Finland

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LIST OF ABBREVIATIONS

ALARP	As low as reasonably possible
AC	Alternating current
BMS	Battery Management System
CAN	Controller Area Network
CFC	Continuous Function Chart
DC	Direct current
ECU	Electronic Control Unit
EDC	Electronic Diesel Control
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EUC	Equipment under control
EUT	Equipment under test
EV	Electric Vehicle
FO	Fail-operational
FR	Fail-reduced
FS	Fail-safe
FSM	Finite State Machine
HCU	Hybrid Control Unit
HEV	Hybrid Electric Vehicle
HV	High voltage
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LV	Low voltage
PLC	Programmable Logic Controller (in relation to physical devices)
RESS	Rechargeable energy storage system
SIL	Safety Integrity Level
SRE	Safety Related Equipment
ST	Structured Text
UNECE	United Nations Economic Commission for Europe
VECU	Vehicle electrics and electronics control unit

1 INTRODUCTION

While the electrification of vehicle powertrains seems to be a fast growing trend, the slow development of rechargeable energy storage systems (RESS) is still holding back the rapid spread of electric vehicles (EV). One of the main disadvantages is the RESS operational range. To extend the range one would need a bigger battery, which in turn brings in more weight and wastes space. In cold environments, the battery power would be reduced dramatically without a pre-heating system, which in turns adds to the overall energy consumption.

A hybrid electric vehicle (HEV) can help to combine the best properties of both electric drives and the internal combustion engine (ICE). The hybrid is not fully dependent on the limited electric power storage. The idea is to combine two power sources to overcome to shortcomings of either of these technologies used on their own. (Reif et al. 2014, 724)

There are common hybrid configurations and new innovative solutions are being tested. In a series hybrid, electric power is generated using an internal combustion engine to drive a generator and the powertrain itself is operated with an electrical drive. In a parallel hybrid configuration, both power sources can be operated simultaneously to drive the powertrain and a generator operation of the internal combustion engine is possible. This solution requires a transmission or other power line strategy because of the internal combustion engine and its limitations. In order to combine these two technologies in one vehicle, all components of both systems are required, and they can be linked together by a mechanical clutch. This is called the series-parallel hybrid. It enables independent series and parallel operation, and combined operation with two electrical machines. A power-split hybrid also combines series and parallel operation using a planetary-gear transmission instead. The Toyota Prius utilizes this kind of technology. The adverse effect of the increased weight in series-parallel hybrid would not always be tolerable in a small vehicle, but the concept might be usable in a heavy commercial vehicle. (Reif et al. 2014, 727-732; Immonen et al. 2012)

In designing a hybrid system, it is very important to observe the conditions of use and duty cycle of the vehicle. Some vehicles with an internal combustion engine can be rather effective, for example, an intercity bus that is driving long distances between stops, whose engine runs on high efficiency during travel. However, energy efficiency of a similar configuration in city bus use would not be very desirable. Constant stopping and accelerating consumes considerable energy, and the internal combustion engine load

does not permit the engine to operate within the range of best efficiency. The energy efficiency during acceleration from stop with an electric drive generally has more than twice the efficiency of a comparable internal combustion engine with a separate transmission (Immonen et al. 2012). A fully electrically operated bus would require charging from an external network and preferably, the charging should be done rapidly in order for the bus to operate without long interruptions. However, the investment costs of an opportunity-charging infrastructure may be high and limit the variety of vehicles compatible with the chosen charging system.

Combining series and parallel hybrid technologies would allow boosting the overall efficiency of a bus to a new level (Immonen et al. 2012). In spite of discarding the external charging equipment and adding more freedom, the use of a more compact battery would compensate for the added vehicle weight of the engine and generator, and it would still be possible to drive emission-free in selected regions.

The CAMBUS idea was to create a series-parallel hybrid powertrain, which combines a diesel engine with a greatly reduced displacement, and an electric drive capable of providing all the propulsion power required. Figure 1 shows a 3D model of the CAMBUS powertrain components. According to the simulations run by Paula Immonen, the CAMBUS powertrain concept seems very promising for a city bus. The results propose that a city bus would benefit from hybridization using a radically smaller diesel engine and the estimated results promise significantly less average fuel consumption than in a regular city bus driving cycle. To verify the simulation results, LUT decided to build a proof-of-concept vehicle. (Immonen et al. 2012)

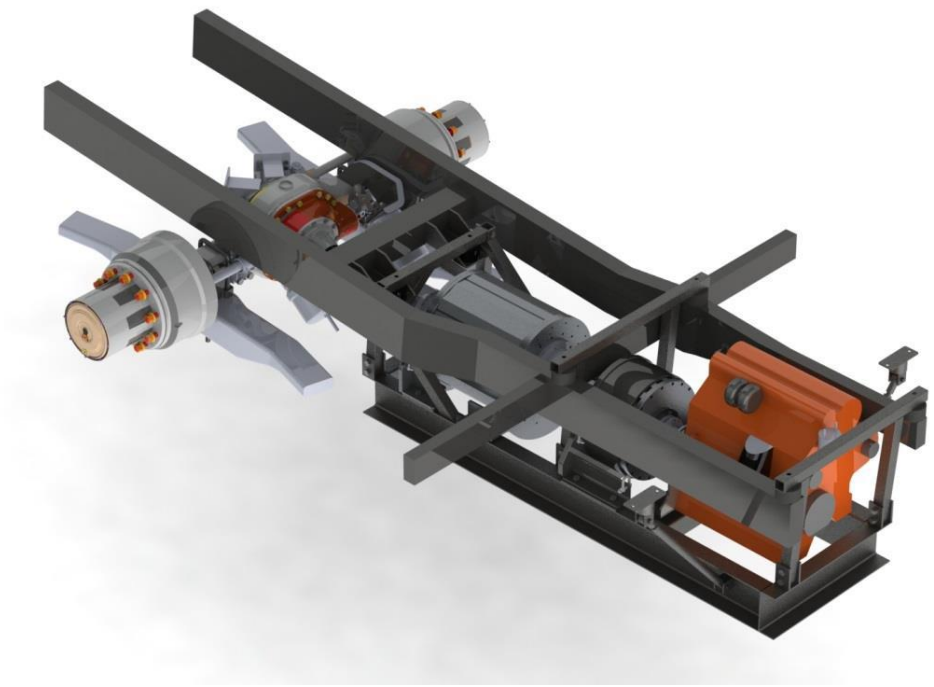

Figure 1. A 3D-model of CAMBUS powertrain. (Teemu Sairanen, CAMBUS project)

LUT has declared itself as a green university, supporting the ideas of recycling and pursuing energy efficiency. A retired city bus was chosen as the basis of the new hybrid technology. Soon the powertrain technology was being planned.

1.1 Goals

This work was an engineering subproject for the CAMBUS main control system development project. The aim was to design and implement software for a control system and use structured methods of testing to demonstrate that the system is safe enough for public driving and taking passengers. During the progress of this work, the user requirements had to be assessed several times, as in the beginning it was somewhat unclear what would be the final use of the bus. Some stakeholders wanted the bus to operate independently in regular commuter traffic; some wanted the bus to remain a proof-of-concept operated only by researchers. These decisions, of course, have great impact on the design requirements.

This document will cover the control system, mainly from the perspective of software development, and the forming of the main engineering processes that start from the user requirements and end with a tested, ready-to-run prototype. The main milestone was to get the vehicle registered as a series-parallel hybrid, enabling both the series and parallel

modes, and to be able to operate it on public roads, thus allowing us to focus on calibrating the hybrid control software and achieve real-life measurement data from the use cycles.

The work will present methods for the design process and the results of this project. It will study some industrial design and risk reduction methods to see whether they can be scaled down and implemented effectively with a relatively small organization, for example a research team. It will also suggest enhancements for the future development of the system.

1.2 Scope

The writer was not restricted to one specific role in the project but instead was acting at almost every level of project organization. The main importance of this work was in organizing the control system development project, creating a structured way of proceeding in an automotive project and, as the final goal, to ensure the safe operation of the bus after its commissioning. The whole CAMBUS project was highly ambitious for the first automotive project of this scale at LUT.

Some of the designed software functions have yet to be implemented and will not be completed during the time allocated for this work. This, of course, limits the scope of this work.

The technical system architecture was planned only regarding the automation, but was sketched to provide an adequate plan for the later testing phase. The implementation of the automation covers the requirements defined by the risk assessment process. As for the testing, the final validation testing is not covered by any other means than planning some of the test procedures.

The technical capabilities and suitability of the pre-selected equipment and engineered systems were not evaluated, only their basic functionality is covered by the test plans created.

1.3 Terminology

Automotive terminology can sometimes be problematic. The writer has tried to adhere mainly to the terminology of regulation 100 given by the United Nations Economic Commission for Europe (UNECE), later referred to as ECE-R100. This text primarily uses

the terminology of the ECE-R100 2012, if not mentioned otherwise. However, a careful reader would notice that even the original UNECE publications have some contradicting terminology and abbreviations.

The automotive legislation, compared with the European Union Low Voltage Directive, has a different approach to defining *high voltage*. According to ECE-R100 a voltage of 60…1500 VDC or 30…1000 VAC is declared high voltage (UNECE 1997). Again, in this text the ECE-R100 definitions are used exclusively. In this document, the high voltage system is referred to as HV, sometimes in conjunction with AC or DC referring to the type of current in question. Similarly, the 12 or 24 volt systems are referred to with the abbreviation LV, low voltage. In accordance to the terminology of the regulation, the term isolation resistance is used instead of insulation resistance.

1.4 The structure of this document

The design process will be examined in more detail after the introduction (Chapter 1). The text uses actual project-related information as examples to enlighten the meaning of the processes. Section 1.6 looks at the process of gathering the design requirements, including risk analysis, and the main safety concepts and considerations. Chapter 3 then discusses the logical system architecture, from which the technical architecture solution is formed. The software design process is then described in more detail.

When implementation is complete, Chapter 4 will enlighten the reader on the methods of testing used during the validation process. Subsequently, in section 3 of chapter 5, we shall take a case example of the implementation of the accelerator pedal and the safety features related therein. The next section explains the immediate results from the different phases of the process. Finally, chapter 6 will express the writer’s subjective thoughts on the project in the discussion.

1.5 The core process

The nature of this work is systems engineering rather than scientific research. The writer chose to follow the structured methods suggested by Jörg Schäuffele and Thomas Zurawka as the basic guideline for the project. It is an interpretation of the common V-model (essentially the same as in ISO/IEC 12207 and ISO 26262), taking into account the requirements for an automotive software project, its methods and relevant safety standards. Various standards were used for further guidance and they will be introduced

later in the text. Because the project did not design or manufacture any electronic devices, the model is used to guide the design and implementation of the software and system levels. Figure 2 represents the core process of this project. Each box of the figure presents a sub-process explained in more detail in the relevant chapters of this document.

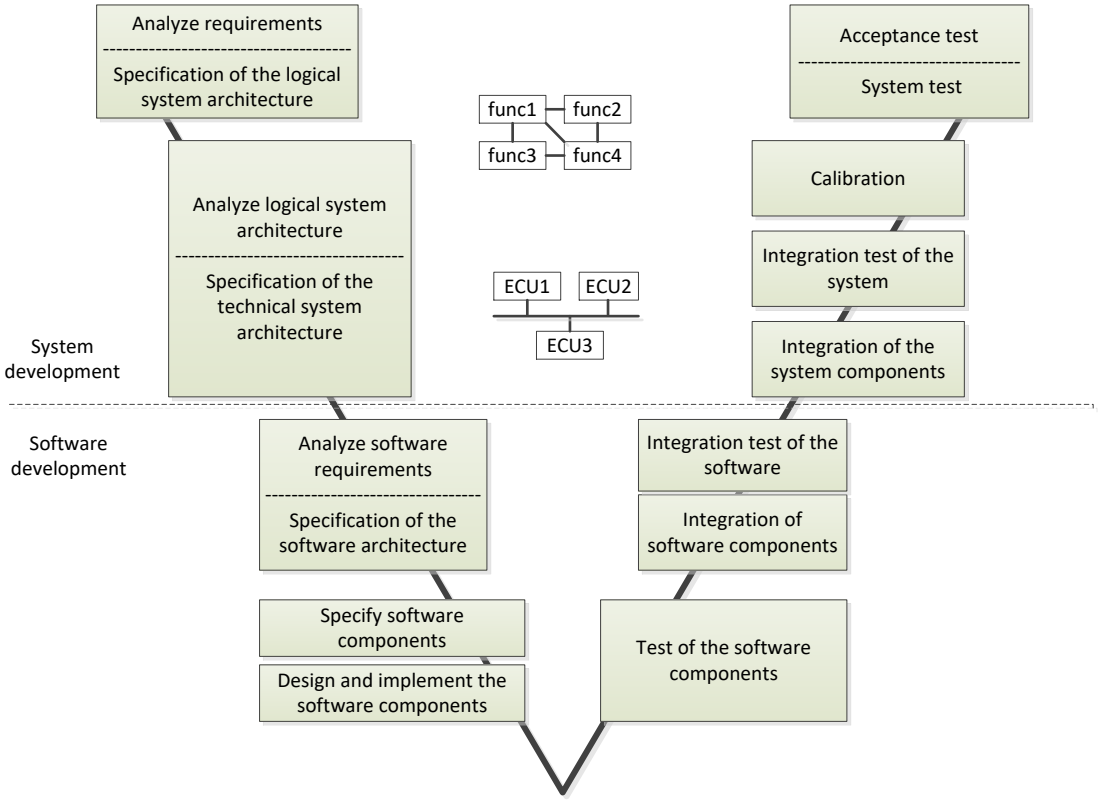

Figure 2. Overview of the core process for the development of electronic systems and software. (copied according to Schäuffele et al.) (Schäuffele et al. 2013)

The left half of the V is explained in chapter 3. The first step of this model begins by the determination of the user requirements, from which a logical operating plan for the system is created. At the next level, the equipment capable of executing and materializing all these logical operations are chosen or designed. This level is called the technical system architecture. Finally, the software architecture is planned according to the requirements set by the technical system architecture and the properties of the chosen equipment. (Schäuffele et al. 2013)

In contrast, testing follows an opposite path, where first the software functions and modules are tested. When the individual components work according to the plan, they are being integrated and thus the system is tested for the first time as a whole. When everything works as expected, the process will move to fine-tuning the system, to

thorough use tests in actual environments, and finally to an acceptance test to prove that all the requirements have been fulfilled. Chapter 4 presents the testing process. (Schäuffele et al. 2013)

Some new matters could appear during the process, introducing new risks or requirements, and then all levels of the plan must be updated accordingly. Thus, it is very important to spend some time in the beginning to build a good foundation through thorough planning. The more experienced the design team, the more thorough the plan, which will minimize unnecessary iterations at a later stage. Safety is one of the main concerns, and as for the planning, it would be beneficial to have a safety-oriented way of thinking throughout the process. (Schäuffele et al. 2013)

1.6 About the preselected equipment

The basis vehicle is a 1997 Volvo B10BLE Säffle city bus. Its engine compartment had a small fire hazard, but the original project team came up with an ambitious plan to resurrect the vehicle with new high tech equipment. Its engine and transmission were removed and the car was acquired almost free-of-charge. The simulations had already given direction to the requirements for the engine power, as well as battery capacity and generator power.

It was not possible to fully follow the V-model process as some of the equipment was already chosen. With a thorough user-requirements study and a thorough study of the available technical solutions, different choices could have been made. The management of the automation project had already decided to use ABB AC500 XC series programmable logic controller (PLC) devices for the control system prototype. It was later understood that they do not fully comply with common automotive design recommendations, but they allow flexible prototyping and programming.

The programming environment consist of the ABB provided Control Builder, which combines the PLC configuration utility and Codesys development environment. The Control Builder software manages hardware configurations, for example input maps and CAN bus communication buffers, and links the relevant variables and ABB software libraries directly to the Codesys environment. Codesys implements the languages defined in the standard IEC 61131-3, which defines the programming languages for programmable controllers. The standard includes both graphical and text-oriented programming possibilities. The Codesys software allows online debugging, controlling and monitoring of the PLC units over the Ethernet network of the vehicle.

It was decided early on, that there would be two controllers because of the long distances within the vehicle: one in the front and one in the back of the vehicle. After the first sketches, their functionality would be quite obvious already. As the front unit would handle all the driver related and most of the chassis related inputs and outputs, it was named the “vehicle electrics control unit” or VECU, and as the rear one would handle basically all of the hybrid system components, it was named “hybrid control unit” or HCU. The network topology of the equipment was planned as an assignment in a system engineering project work course. Figure 3 shows an overview of the system topology. As we can see from the picture, there are several features related to the vehicle electrics, mainly made by Volvo and the body manufacturer Säffle, but also the control units for the Wabco Anti-locking Brake System (ABS), including Anti-Slip Regulation (ASR) functionality, and Bosch Electronic Controlled Suspension (ECS).

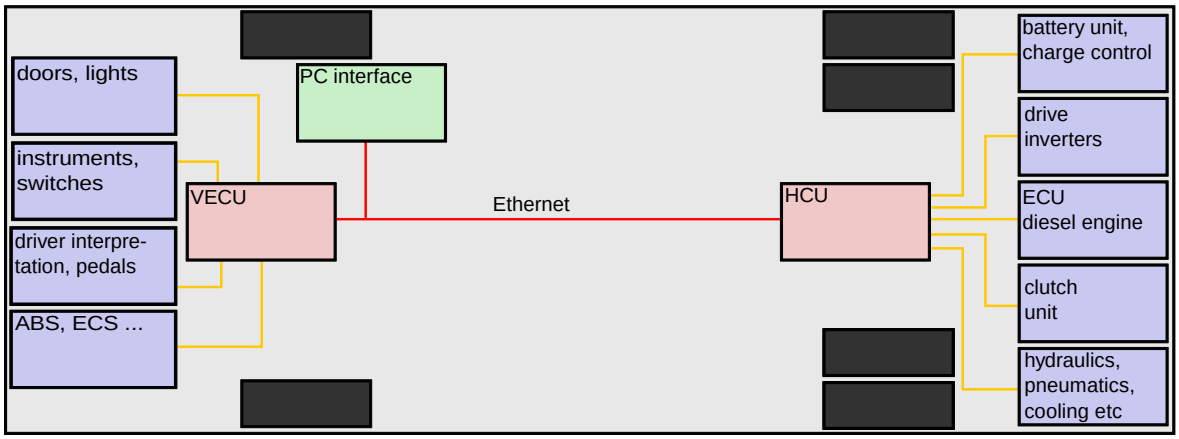

Figure 3. A simplified model of the system topology and the network buses.

There are automotive control units available that also support IEC 61131-3 programming and likely the system programs could be ported to this platform with reasonable effort. The current software solutions are explained in detail in section 5 of chapter 3.

At the time the equipment was selected, inverters designed for automotive applications were not easily available. Visedo PowerMASTER inverters were chosen because they fulfilled the environmental requirements, they have versatile internal application programmability and are capable of driving a six-coil traction motor with two parallel inverters. A third inverter of the same product family is used for operating the generator. There is also a combined inverter and DC/DC converter to operate the air compressor motor (HV) and to supply the 24 V DC (LV) system. These inverters support the user applications created in an IEC 61131-3 compliant programming environment. One

additional auxiliary drive inverter for the motor of power steering hydraulic pump is from ABB.

The battery system consists of lithium-titanate cells and a management system manufactured by Altairnano. A Bender isolation monitoring device designed for automotive applications was chosen to be incorporated into the BMS and control system safety functions.

The main components of the high voltage system are shown in Figure 4. The isolation resistance monitoring device was planned to be integrated in the battery unit.

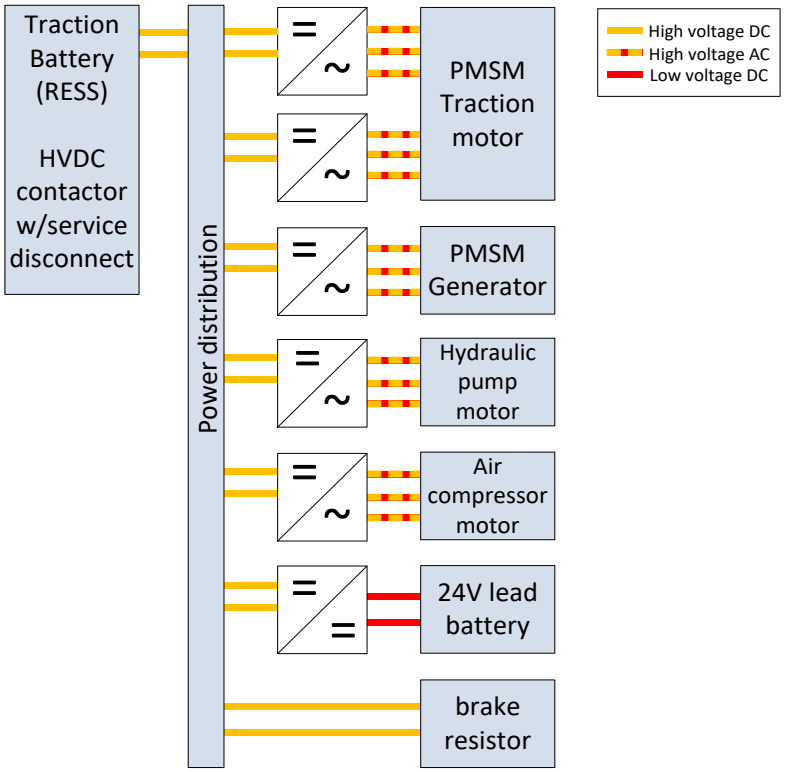

Figure 4. The high voltage system components. PMSM stands for permanent magnet synchronous machine. The DC-DC inverter is used for supplying the LV DC and charging the 24 V lead batteries.

The internal combustion engine is a Volkswagen diesel engine unmounted from a regular van. An industrial diesel engine would have been preferable but was deemed too expensive in the initial proof-of-concept phase. The engine came from a 2002 Transporter with an intercooled 2.5-liter 111 kW turbo diesel engine, emission category EU3.

2 THE DESIGN REQUIREMENTS

This chapter will deal with the initial function development, which includes the gathering of the design requirements for the system. Each section represent a chronological step in selecting the final design requirements.

As the vehicle was destined to road use, we shall first look at the legal requirements that will be the foundation for the rest of the user requirements. Then we shall cover the process of selecting the user requirements for the design process. These requirements require technical solutions that lead us to the risk assessment process. The iterative process looks into all solutions in detail and may suggest modifications or safety features to be added. These are considered the design requirements for the actual design process as well, which will be covered in chapter 3.

Some user requirements were already decided upon in the first conversations, but in order to proceed systematically, these more or less documented requirements were organized. This was done by first identifying the user groups and making several user requirements surveys in the form of informal conversation and interviews. A map of requirements was created and then the final requirements were selected from those suggested. The user and the legal requirements would be the basis for designing the logical system architecture. In addition, the risk management process and experience gained throughout the project would add requirements that are more detailed iteratively. Figure 5 shows the requirement categories identified by the team responsible for the functional development.

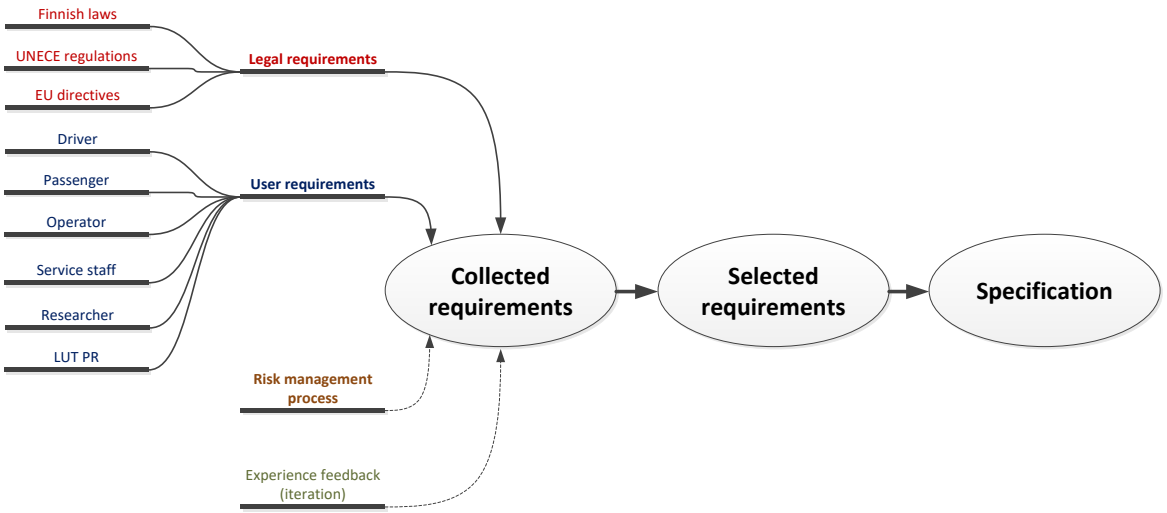

Figure 5. The requirements stem from multiple groups that may each have greatly different wishes and requirements. The specification for the system will be created from the “selected requirements”.

2.1 Legal requirements

Legal requirements are a vitally important part of gathering the design requirements as they pose direct and indirect demands on the hardware and control software. Therefore, this should be done first. The writer would like to emphasize that this should be the very first step to overcome any later surprises and major setbacks in the design process, and thus suggests an early cooperation with transport authorities. The vehicle must be inspected and re-registered once it has been modified. The legal requirements are there for a reason and all the vehicle modifications must be approved by the respective authorities. It helps to maintain good documentation practice throughout the project so that the inspection authority is able to easily investigate the changes and sign an approval**.**

Amongst the many regulations related to the CAMBUS project, the following regulations were relevant for the software project. The most critical are listed in Table 1. The indicated Finnish regulation enforces the ECE-R100, which lists a number of detailed requirements for electric vehicles.

Table 1. Regulations relevant for the software design process.

Regulation	**Description of the regulation**
Finnish Ministry of Transport and Communications: Regulations concerning the structure and equipment of vehicles and trailers 19.12.2002/1248 changed with 30.9.2011/1064 (Available in Finnish and Swedish)	18 a § (30.9.2011/1064) Regulations for vehicles with electric powertrain.
UNECE R-100	Regulation 100, Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric powertrain

2.1.1 Electrical safety and electromagnetic compatibility

When talking about electric vehicles, there is obviously a great concern for electrical safety. In Finland, when there is no plug-in charging implemented, the electric safety of an EV is mainly regulated by ECE-R100. It sets the guidelines for general electric safety and isolation, the rechargeable energy storage system (RESS), functional safety, and crash safety (UNECE 1997). Because of its importance in the project, we will discuss the ECE-R100 requirements in more detail in the next chapter. Within this project, the Low Voltage Directive covers only work safety while working on the vehicle.

For such an old vehicle, the authorities do not require any official EMC test document, but the vehicle must still comply with the regulations that were in force when the car was registered the first time. For safety reasons in general, it is naturally advisable to make such measurements to make sure that the electromagnetic interference from the vehicle power systems do not cause any danger to the passengers or people outside the vehicle.

The final commission is done by a qualified person, who must sign approval that all the electrical systems of the vehicle comply with the regulations.

2.1.2 Requirements per UNECE R100

The UNECE has created a regulation concerning the approval of battery electric vehicles. This was the most important electric-vehicle-specific regulation for the project vehicle. As per the first date of registration of the vehicle, the revision 2 addendum 99 was used as the basis. It sets requirements for specification and testing, and for the alteration of this older vehicle, the requirements can be divided into two categories: the construction requirements and functional safety.

The construction requirements concern the RESS and all parts of the high voltage bus. Naturally, the main concern is the electrical safety: the methods of protection against direct or indirect contact with live parts, and demands for the isolation resistance. It also explains the methods for testing against the possibility of hazardous contact and the measuring of the isolation resistance. (UNECE 1997)

The functional safety includes a list of obligatory features and functions that must be implemented. For example, it states the requirements for how the driving mode is activated, the requirements for the instrumentation and warning signals, and the safety functions against unwanted acceleration. As a reference for the accelerator safety requirements, the ECE-R100 dated 1997 states in section 5.2.2.4 that “a failure (e.g. in the powertrain) shall not cause more than 0.1m movement of a standing unbraked vehicle” (UNECE 1997). This was used as a design reference for accelerator safety and is covered in more detail in section 5.3.4.

2.1.3 Service brake and steering

It was decided early on that the original service brake, steering systems and components related to either, would be preserved as much as possible and only the power supplies for these systems were replaced by electrical equivalents. The functionality of the related original control units was preserved and exploited by the new control systems, where possible, in order to enhance driving safety. The changes to the steering and brake system must be documented, and the functionality of the brake system must be demonstrated and proved during the registration inspection, and during the vehicle’s annual inspection.

2.2 Risk management

In a project of this magnitude and because the outcome is a product that will be used in public transport, a risk management process must be defined. Optimally, this process should be active from early on and it may be integrated into the quality management of an organization. At the least, the strategy of risk assessment and risk reduction should be integrated into the design processes. The identification of use cases and risk was first done following the ISO 12100 standard and the guiding document SFS/ISOTR 14121-2. In principle, the standard is for machine safety, but was found to be adaptable to this part of the project. The design process also takes controller and software-relevant standards into account. The relevant standards are listed in Table 2.

Table 2. The most relevant standards for the software design process.

Standard	**Description of the standard/part**
SFS-EN 12100	Safety Of Machinery. General Principles For Design. Risk Assessment And Risk Reduction
SFS-ISO/TR 14121-2	Safety Of Machinery – Risk Assessment – Part 2: Practical Guidance And Examples Of Methods
IEC/TR 61508-0	Functional safety of electrical/electronic/programmable electronic safety-related systems. Part 0: Functional safety and IEC 61508
SFS-EN (IEC) 61508-3	Functional safety of electrical/electronic/ programmable electronic safety-related systems. Part 3: Software requirements
SFS-EN (IEC) 61508-4	Functional safety of electrical/electronic/ programmable electronic safety-related systems. Part 4: Definitions and abbreviations

ISO 12100 states: “the risk assessment is a series of logical steps to enable, in a systematic way, the analysis and evaluation of the risks associated with machinery” (SFS-EN ISO 12100 2010). The main term risk assessment is divided into two subjects. The first comprises of *risk analysis*, which covers the first three steps described in the section 2.2.1. The fourth one is called *risk evaluation*. After the risk has been evaluated it is assessed by the risk reduction process, which is introduced in more detail in section 2.2.2.

To help clarify the functional relationships of these processes, see Figure 6 for a flow chart of the risk assessment and reduction processes.

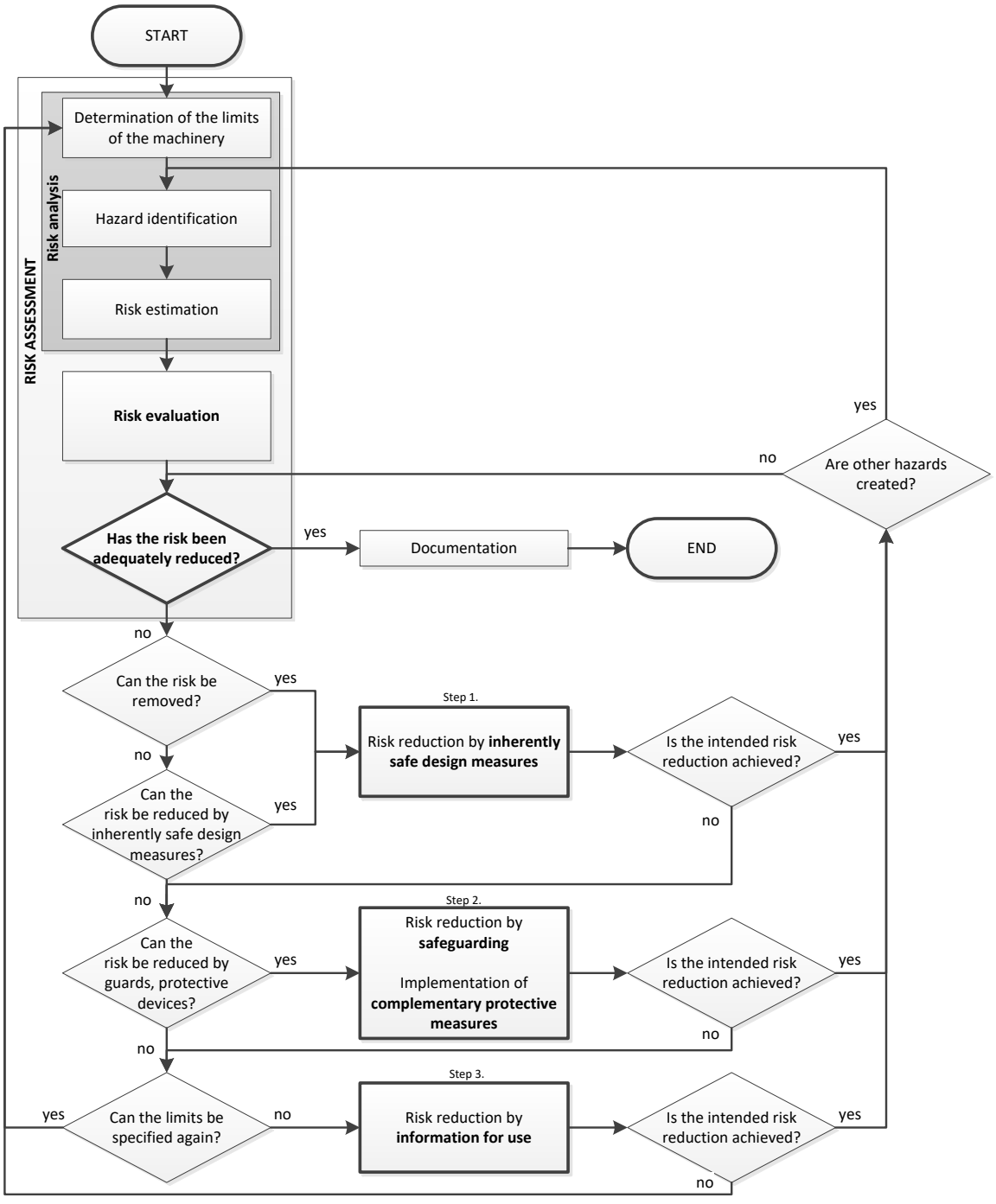

Figure 6. The risk assessment and reduction processes. (Figure copied according to ISO 12100) (SFS-EN ISO 12100 2010)

2.2.1 Risk analysis

According to SFS-EN ISO 12100, the risk analysis begins by determining the limits of the machinery. This must include the intended use and reasonably foreseeable misuse. In a vehicle, this would be analogous to any abnormal way of operating, for example excessive pumping of the accelerator pedal while driving, an excessively long time with full power, using controls in abnormal way and so forth. The system must always be able to handle the requests from the driver controls to operate the vehicle in a safe way, and the subsystems must be able to reduce their operation or go into a fail-safe mode to prevent a breakdown, and avoid hazards or hazardous situations. (SFS-EN ISO 12100 2010)

The next procedure is identifying the hazards related to the machinery, and the associated hazardous situations (SFS-EN ISO 12100 2010). There are readily available checklists to help the assessment process, for example in the standard ISO 12100. These lists help in obtaining an overall view of the risks and their root causes and how to eliminate or reduce them.

When the hazards and hazardous events have been identified, the associated risk must be estimated. In this case, a method called risk graph was used. The risk graph method assess severity, frequency and probability of an event, and the possibility to avoid it. The result of this assessment is the risk class, which is given different safety integrity levels. When all the risks have been estimated, they must then be evaluated to determine the methods required to reduce the risks to an accepted level. (SFS-EN ISO 12100 2010)

The standard IEC 61508 deals with risk management in conjunction with the electronic control equipment. However, the reliability estimates mentioned in the IEC 61508 were not available for the majority of the preselected and original vehicle components. The risk assessment was thus executed regarding personal estimates of the assessment group. Because of limited resources, the failure mode and effects analysis (FMEA) was omitted.

2.2.2 Risk reduction

Risk reduction follows risk analysis. The risk reduction process refers to the elimination of hazards to an acceptable level by using so-called protective measures. The protective measures may be anything from safety covers to instruction manual. It may be necessary to repeat this process iteratively in order to reach the predefined level determined as acceptable risk. This level is usually referred to as ALARP, which is an abbreviation for “as low as reasonably practicable”. ALARP tools observe several factors, for example,

codes and standards, cost benefit versus risk assessment, good practices and benchmarking. The ALARP assessment was greatly simplified because of the lack of resources, and the project team determined the accepted level loosely. (SFS-EN ISO 12100 2010)

Protective measures are divided into those implemented by the designer and those implemented by the users. According to the standard, the designer is responsible of implementing protective measures, which can be further divided into three sub-measures: inherently safe design measures, safeguarding and complementary protective measures, and information for use (SFS-EN ISO 12100 2010). The first consists of all the regular safety aspects of the design, from choosing the technology to ergonomics. In addition, the electrical safety is a part of this step. The basic requirements for the electrical safety are set by the ECE-R100, so the residual risk should be evaluated after fulfilling its requirements.

The second measure mentions safeguarding and complementary protective measures, for example the emergency stop switch. In addition, the protection from live contact required by ECE-R100 is a part of this design category. This would include all sorts of shields, covers and detecting the state of these safety features by an isolation resistance-monitoring device, similarly as to what ECE-R100 requires from the fuel cell vehicles (UNECE 2013). As for the control system, it must include basic diagnostic and protective features. (UNECE 1997)

The third measure relates to instrumentation. For the user, the levels of risk reduction include the user organization and its safety culture, training the users (driver, service personnel) and training the rescue teams that may have to work on the equipment after an accident.

The results of the ISO 12100 analysis were used during the design process for the logical and technical system architectures, as well as for the basis of software architecture planning. As most of the hardware components were preselected, and the scope of this work was limited to software implementation, the actual technical components and the physical implementation of the technical system architecture is covered only as seen necessary to help understand the software development process and requirements therein. The requirements for the software design were further refined using the principles of IEC 61508-3. The standard IEC 61508 will be briefly introduced in section 2.4 concerning the functional safety of the equipment.

It is rather obvious that some new risks and dangerous situations are detected during the development processes, at the latest during the actual testing and use, but the majority of the risks related to the control system and equipment under control can be thought of before proceeding with the actual construction. As the nature of the risk management process is iterative, there must be effective means to document the requirements, control the development process and maintain a revision history for all the documents involved in the development process. This, of course, helps to plan the SRE and safety architecture as early as possible. (Schäuffele et al. 2013, 198)

An example of the risk assessment documents is shown in the Appendix I. It includes a part of the forms used in risk identification, risk assessment, risk reduction and risk evaluation after the risk reduction process.

2.3 Typical risks

In order to begin identifying risks, a literature search was carried out and revealed two Finnish reports related to bus fire incidents. The earlier report was published in 2010 by the Technical Research Centre of Finland (VTT) and concentrates more on overall safety enhancements (Kallberg 2010). The Finnish Traffic Safety Authority (TRAFI) has published more detailed statistics and analyzes of bus fire hazards between 2010 and 2012 (Kokki et al. 2013). These reports were examined to better understand the most common causes for bus accidents and what would be the obvious risks to which to pay attention. Neither of the reports cover the newer hybrid or fully electric buses. In addition, the author consulted a technical specialist at an insurance company and the vehicle systems were examined together to find any suspicious implementations and potential risks (Makkonen 2015).

The three major risks categories were identified as fire hazard, road accident and electric shock. According to the report by Kokki et al., the main reasons for fire hazards are mechanical overheating (brakes, bearings), malfunctions in the electrical systems or short-circuiting due to failing electrical insulation and oil or fuel leaks on hot engine components (Kokki et al. 2013). According to the specialist, the fire risk in the engine bay is amplified especially if the engine bay is not regularly washed and flammable substances and dust are allowed to accumulate on the engine. The insulation problems can result from abrasion, as there is a lot of vibration present during the use of the vehicle, but also chemical and thermal exposure, or aging (Makkonen 2015). The humidity in the air affects the isolation resistance, as well, and can easily render the situation even worse.

Inevitably, the risk of short-circuit is also a risk of electric shock in the case of high voltage equipment in an electric vehicle. Thus, the importance of proper wiring, shielding and cable support should be stressed. By the requirements of ECE-R100 and common practice, the cables connected to the HV system are color coded orange (UNECE 1997). It is also to be noted that the risks of these dangerous situations may accumulate from each other.

The ECE-R100 regulation describes the requirements for protection against contact with a part that has dangerous voltage and the appendices describe means to test the conformity of the protection (UNECE 1997). However, this is more related to the design of the technical system architecture.

The regulation also describes test methods that must be used to measure the isolation resistance of the system (UNECE 1997). The ability of the control system to react to a HV insulation problem relies on an isolation resistance-monitoring device that constantly monitors the resistance between the HV system and vehicle chassis. Depending on the failure mechanism, the inverters may be able to detect a problem with the motor wiring and consequently cancel their operation internally.

The failure mechanisms related to the possible origin of the above-mentioned dangerous situations are linked to the software design by means of detecting these situations in order to prevent greater problems. This may include the fault messages from the functional modules or dealing with the symptoms of a blown fuse or a broken relay.

2.4 Functional safety of the control equipment

The IEC 61508 standard is a functional safety standard, which has been applied to various industries. According to the definition in IEC-TR 61508-0 the “functional safety is part of the overall safety that depends on a system or equipment operating correctly in response to its inputs” (IEC/TR 61508-0 2011, 10). It covers hardware failures, operator errors and environmental changes. The title of the standard IEC 61508 refers to the functional safety of electrical/electronic/programmable electronic safety-related systems in general. While this standard was used for the automotive applications as well, the recently created ISO 26262 is specifically for the functional safety of road vehicles. Both of these standards were observed, but they were discovered too heavy for the project’s needs. The methods of IEC 61508 were observed together with Schäuffele at al. (2013) to form a semi-formal method suitable for the minimal resources of this project. Specifically, the

guidelines for the software design methods of part three were used during the specification and verification processes. IEC 61508-3 also gives guidelines on risk reduction during the software design process. (SFS-EN 61508-3 2011)

One key difference in the philosophy of IEC 61508 and ISO 26262 is how they see the equipment under control (EUC), the safety related equipment (SRE) and equipment under test (EUT). In IEC 61508 they are separate while in ISO 26262 they are more integrated. IEC 61508 was not developed for the needs of automotive engineering and usually in the control topology, it is sensible to integrate the safety features directly into the control system itself. (Reif et al. 2014, 254; Schäuffele et al. 2013)

The risk level correlates to safety integrity level (SIL) which determines the methods of engineering to reduce the risks to a predetermined accepted level. The SIL levels are numbered from 1 to 4. For example, usually, in a car with a drive-by-wire system the engine control unit reads the signal from accelerator pedal and controls the engine to fulfill the driver's request. Safety is typically approached here by adding diagnostics that utilize both hardware and software functions. In more advanced systems, everything is doubled so that the system can analyze and determine if either one of the input signals is plausible and to continue safe operation. Usually all the hardware from the power supplies of the position sensor to the A/D converters are separate. While this sounds already quite safe, the equipment itself may not be perfectly stable and the higher SIL2 (or ASIL2) categories practically require equipment that monitors the control equipment itself (EUT). These systems include a separate RAM memory, a processor that runs identical code, and a system that compares the results between the processors. According to the IEC 61508 part four, its purpose is to detect internal hardware failures and so-called transient soft-errors occurring "in the memory, digital logic, analog circuits, and on transmission lines, etc. and are dominant in semiconductor memory, including registers and latches" (SFS-EN 61508-4 2010). An industrial PLC complying with the IEC 61508 SIL2 requirements would generally be called "a safety-PLC". Embedded processors capable of internal monitoring are also easily available. (Schäuffele et al. 2013)

The system redundancy architecture is commonly referred to by the term MooN or "M out of N". It describes the level of redundancy involved with number replacing the letters M and N (Schäuffele et al. 2013). For example, 1oo1 (1 out of 1) means that there is no redundancy involved, as only one input is used. Using a 1oo2 architecture instead, the safety fault tolerance can be increased, as there are two input values that can be voted upon. However, the availability of the equipment may not be increased if there are no

means to continue safe operation while the other input is declared faulty. This can be addressed by adding diagnostic functions. The diagnostic capability is marked with a trailing letter D. For example, in a 1oo1D architecture, the quality of the input signal could be monitored according to a behavior model, and in case the diagnostic system detects a fault, it can independently deactivate the module output.

The risk assessment was done first to collect the obvious design requirements and later on as many times as necessary until the risk had been reduced to an accepted level. The process in its entirety has been described in its own documentation and the forms produced by the process are archived by the CAMBUS project.

3 THE SYSTEM AND SOFTWARE DESIGN

This chapter will examine how the left side of the formerly introduced V-model proceeds systematically, and has a detailed look into each step. At the end of this chapter, the software is set up to work together and the fourth chapter shall proceed with tests from the right side of the V-model.

Writing the specifications may be time consuming in the case of a complex system with nested functional interactions and demands for fault tolerance and diagnostics. The legislation is the foundation for the vehicle safety requirements. The user-interface-related functionality is mainly derived from traditional solutions in commercial vehicles.

The user interface consists of the instrumentation and the controls. The driver is supposed to receive warnings and fault reports through the instrumentation, and control the system via the controls and switches on the dashboard. Because of the high risk involved, a diagnostic system monitoring the controls and functionality of the system is required to lower the level of risk involved in a drive-by-wire system (Schäuffele et al. 2013, 211-214). The visual instrumentation will present statuses, instructions and messages through a dash display and signal lights. All the functions related to driving, monitoring and coping with fault situations, as well as some functional descriptions, are described in the user manual. In addition, troubleshooting tips and service instructions are gathered in the manual. Because some of the maintenance and service operations might impose serious risks, the manual must give step by step instructions and cover all the related safety requirements, description of tools and use of protective equipment (SFS-EN ISO 12100 2010).

3.1 Logical system architecture

The specification of the logical system architecture is the end-result of function development. In this phase, all the functionality and interaction of the modules in the vehicle must be planned. The logical architecture plan must fulfil the user requirements on a logical level.

The drive system of a HEV requires a far more complex control system compared to the system in a plain EV. There are more devices on-board and numerous operating conditions for both the series and parallel operation, not forgetting their combined operation. The technical functionality must then be coupled by a geographical drive

control system (by a GPS or hard-coded route map), multiple-regeneration-related control algorithms, as well as crawl, hill hold, anti-jerk and slip control algorithms. To add to the complexity, there are also unpredictable changes in traffic situations, weather conditions (e.g. temperature management) and driver habits, which may always produce unexpected behavior. For example, a rapid change of torque direction will easily cause the slack in the powertrain to create noise and a jerking motion, or even damage the powertrain components. Despite the sophisticated system control algorithms, the driver should still negotiate the traffic in a predictive manner to exploit the potential of the hybrid system. (Reif et al. 2014, 773)

A meticulous planning of the architectures is vitally important. The nested modules and systems, their failure mechanisms and the diagnostic functions required to detect the failures, create an abundance of software conditions and algorithms that must work together flawlessly in order for the driver to feel that the vehicle is safe and operating logically at all times. Many of these requirements seem relatively simple when observed independently, but in reality, combining them all together to form a working union is quite a demanding task. Even when the torque control system is able to operate all the drive components properly, the Battery Management System (BMS) conditions for charge and discharge must be observed and the torque requests of the drive components may be forced to be limited accordingly. This means that in a well-designed and tuned system the driver interface (e.g. a simple device like accelerator pedal) masks the complex internal functionality of the hybrid control system. The driver does not need to concentrate on handling the equipment in any peculiar way, but can drive the vehicle just as any usual vehicle and concentrate on the driving and traffic situations.

In addition to the basic features in normal healthy operation, the logical system architecture should already have a plan for the safety logic: fail-safe, fail-operational, fail-reduced. Only at this stage, however, it was determined that a means of monitoring and diagnostics would be required at least for the accelerator pedal, and the internal functionality and implementation of the diagnostics were designed first on a general level. The safety logic is discussed more thoroughly in section 3.3.

3.2 Technical system architecture

The typical order of a design process beginning from scratch would assume that now the technical means to accomplish the requirements set by the logical system architecture are being selected. This phase is a part of the system development phase. As mentioned in

the introduction, some of the equipment was pre-selected and this steered the technical architecture towards a specific topology, where there are two main control units.

Figure 7 presents a brainstorming diagram that demonstrates how the equipment and its functionality are interconnected. The designations used are derived from common automotive terminology.

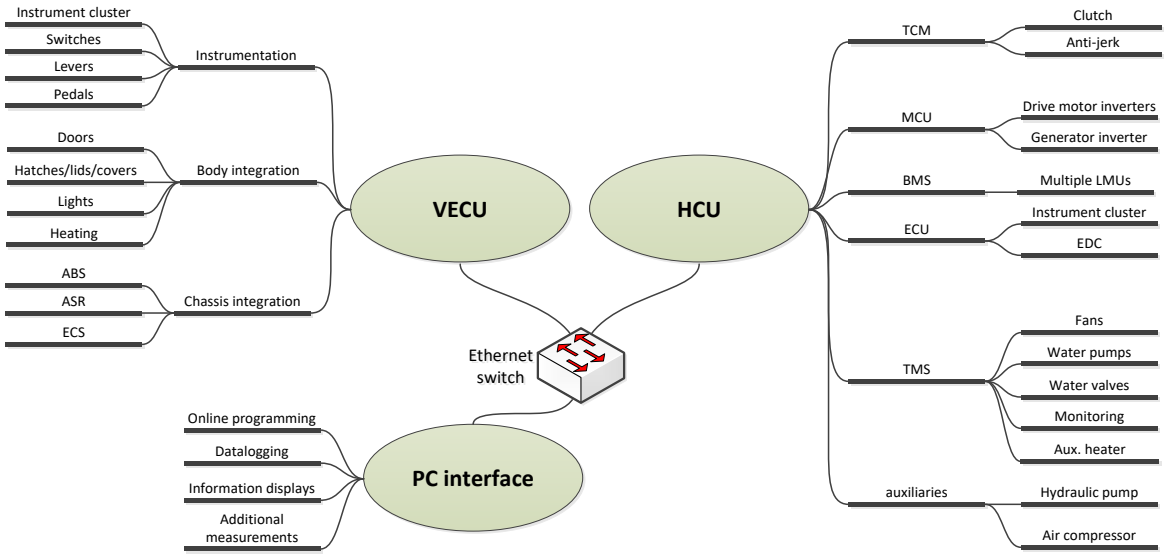

Figure 7. An overall view of the relationships of the specified equipment required to fulfill the specification of the logical system architecture. Abbreviations in the figure: ABS Anti-lock Brake System, ASR Anti-Slip Regulation, BMS Battery Management System, ECS Electronic Controlled Suspension, ECU Electronic Control Unit, EDC Electronic Diesel Control, MCU Motor Control Unit, PC for Personal Computer, TCM Traction Control Module, TMS Temperature Management System.

The communication network topology consists of one main network and several local networks. On the top level, connecting the PLCs and data loggers, there is an Ethernet network, where messages are sent via UDP protocol with CRC checking enabled. The rear end separated CAN networks are hosted by the HCU control unit. The drive inverters communicate via the 29-bit CANopen standard, the diesel control unit via 11-bit CAN 2.0 according to VW CAN version 3, and the battery management unit communicates with CAN via SAE J1939 protocol. The inverter bus operates at 250 kbit/s, while the battery and ECU CAN bus operates at 500 bit/s speed. The VECU unit uses one additional CAN

bus to communicate with the instrument cluster via SAE J1939 protocol, which operates at 250 kbit/s. When configuring the CAN bus, the priorities and transmit intervals must be carefully considered and the bus load must be checked in a real-life situation. The maximum recommended bus load is not unambiguous; depending on the source, values between 30% and 80% can be found. The maximum load depends greatly on the baud rate and type of load. The message synchronization is based on the higher priority messages, and lower priority messages might start dropping if the bus has high load levels (Cook et al. 2008). The three separated CAN buses were all analyzed and considered safe and not dropping any packages. Figure 8 shows a network topology presentation of all the connected equipment.

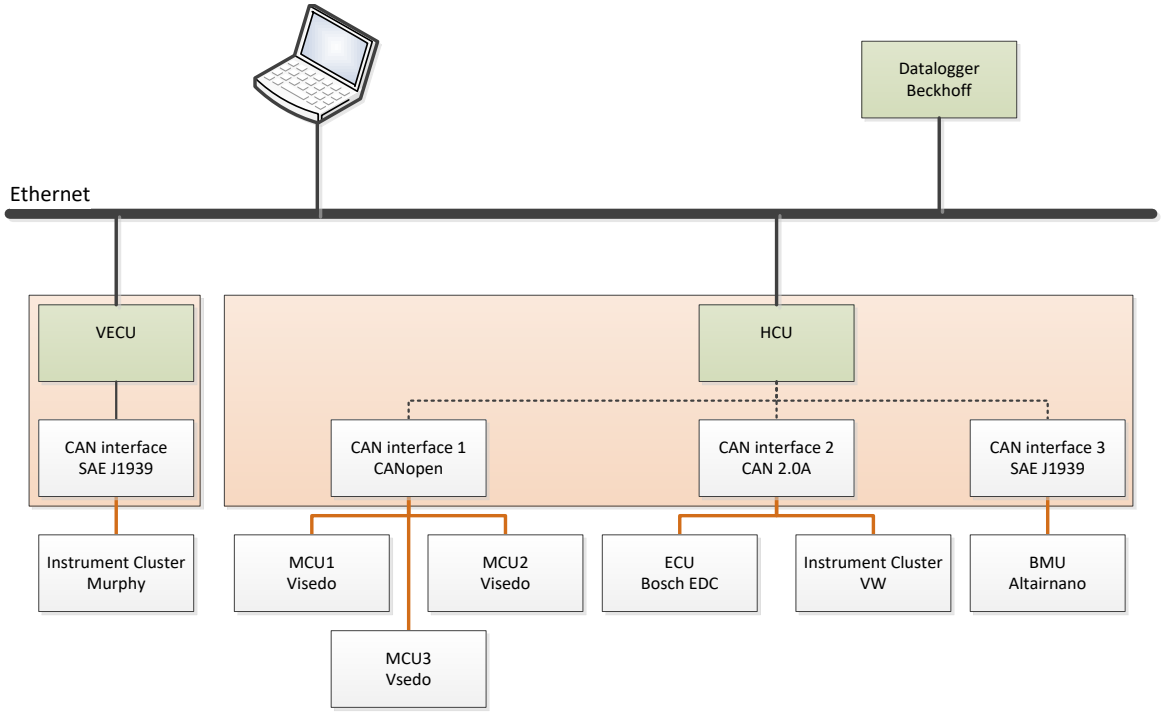

Figure 8. A representation of the physical communication buses. The black wires represent an Ethernet network; the brown wires represent CAN buses. The CAN interfaces are internally connected either to the VECU or HCU PLCs. The BMU relates to the Altairnano Battery Management Unit device.

The success of the communication must be actively monitored because of various signals related to high risks. The decision how to monitor and the desired results in case of a communication error should be based on the risk estimates related to the control parameters and values required by the control system. The input and output system was designed to be as simple as possible to avoid sharing problems. Each input value is

designated to a module handling the input values and writing them to a global register, which the other modules may read. The control of the outputs was limited by coding rules so that the module controlling the output may only get the input value from a specific higher block.

The next phase included considerable detective work to be able to combine all the old body electrics and electronics and integrate them with the new system. This was required to comply with the regulations as well. The EDC functionality and ECU CAN bus messages were studied from a manual called Bosch EDC 15+ Funktionsrahmen. In order to be able to read the ECU CAN bus, the original Volkswagen instrument cluster was required. Without the instrument cluster, or some other control unit sending messages, the ECU CAN state machine would enter error state and cease to communicate (Bosch 2002). However, this allowed us to make use of the instrument cluster CAN messages, as it is reading some of the sensors and signals and broadcasting their values and states over the CAN bus.

3.3 System safety architecture

At this point, the functions, all the possibilities and limitations of the equipment should be known. The previous assessments must provide information of the requirements for the design of the system safety architecture. Regarding the level of safety built-in to the selected equipment, the possibilities of adding safety by software implementation is observed.

Each of the main functions should have a target level of redundancy. The pre-selected components allow a 1oo2 safety architecture for the traction motor inverter control, although as fail-reduced operation in terms of the maximum generated torque available. The torque request signal safety is secured by monitoring the communication pathways and safety signal. Each module in the control chain will monitor the signals it is receiving, but the transmitted data is not doubled. There are no multi-channel implementations that would, for example, allow voting for the inputs in problem situations.

Another drawback is that at the highest level, the selected control equipment cannot analyze its own behavior to ensure flawless operation. The control system would benefit from the use of safety PLC units that run the same program code within independent processors and memories. They would be able to detect internal control unit failures and, depending on the configuration, continue operation to allow continued safe operation or a

safe stop for instance. Today's vehicles typically have dual individual power supplies incorporated for the sensors, they read the sensor values with separate ADCs, the signal processing is done simultaneously with two separate hardware, and the healthiness of the system and its main processes are evaluated internally by dual processor technology. The Visedo inverters have an external stop command signal that is specified as SIL2 class functionality. Additional safety can be achieved by linking this to the PLC and an emergency switch operated by the driver.

Schäuffele et al. (2013) explains the safety logic planning, which requires determining a fail-safe (FS) mode for each unit. For example, from the perspective of the battery management system, FS is a state where the RESS is uncoupled from the main HV DC bus and the internal pack contactors are uncoupled. For the internal combustion engine, it is the state where the ECU is off, and the fuel valve solenoid is de-energized and the generator control is shutdown. For the accelerator system, the torque request is reset whenever a serious problem with the input signals is detected. The other common failure modes are called fail-operational (FO) and fail-reduced (FR). For example, the diagnostic functions of the accelerator module include features that allow resetting the fault condition if certain amounts of cycles have been fault free. This kind of behavior is called fail-operational. If the failure is found repeatedly, the error is marked permanent and the accelerator will enter the fail-safe mode. Typically, this kind of logic could be described as FO/FO/FS, which means to allow resetting twice before entering fail-safe mode. Some equipment can utilize the FR mode, for example, the inverter power output may be limited due to temperature conditions in either the inverter or the traction motor. (Schäuffele et al. 2013, 113)

The more complicated safety measures also add to the price of the equipment so it is necessary to determine the requirements and safety category of each unit. For example, driving an air compressor is not the most critical task in terms of processing power or software complexity. There is not much to do in case of an equipment failure. The compressor system consists of an overpressure relief valve in case the inverter decides to run continuously, and vice versa, in case of the compressor not running, the regulations demand a pressurised air tank that will allow a certain amount of braking with full brake power. The driver must get a warning of the low pressure in the system as well. The requirements must be determined by the sum of all the safety measures in accordance with ALARP. In the end, it is the driver who makes the final decisions while driving the vehicle, thus it is crucial to inform the driver of such failures through the instrument cluster or with a sound signal. This is demonstrated in a simplified flow chart in Figure 9.

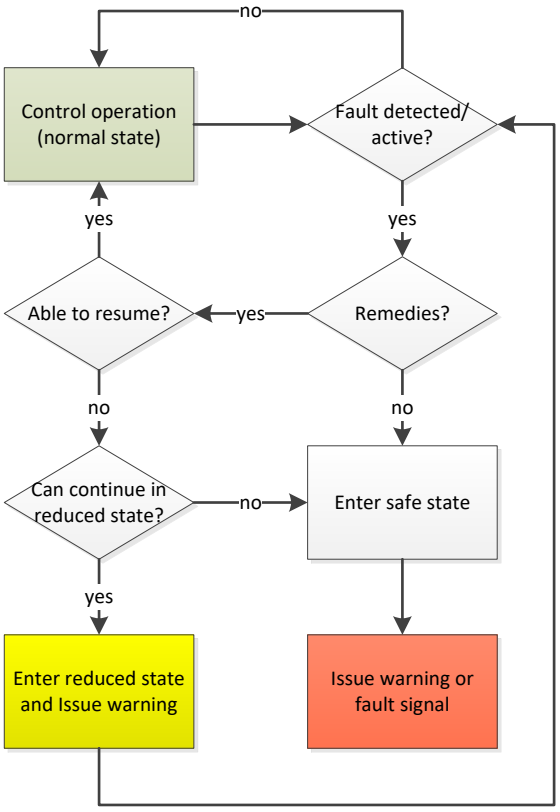

Figure 9. A flowchart demonstrating the principles of a fault handling process. The yellow color of the fail-reduced state represents the warning color in automotive instrument cluster (can still drive) and the red color a major failure or emergency. The safety logic can differ from unit to unit, depending on the risks involved, and some will allow resetting of the fail-reduced or fail-safe state, while some enter fail-safe mode permanently. (Schäuffele et al. 2013, 113)

The software architecture is typically laid out of modules or units. This, observing from the highest level, follows the logic of equipment under control and control system of IEC 61508. In this case, all these control units are integrated into two main control units and the topological relations are mainly dictated by the physical location of the relevant equipment. In a satellite topology, where all functional equipment is controlled by its own control units, one failing unit will not cause the whole of the system to collapse. In an integrated system, there is the danger that in the case of internal failure of the control electronics, the whole system can suddenly behave erratically or cease to function. In any safety critical system, a dedicated safety controller would be beneficial. A thorough estimation and comparison of the reliability of the chosen equipment is however out of the scope of this work.

A good design rule is to simplify as much as possible. There should be a clear logic to as to how the features and functions in the software are controlled, how the data is managed, and where the global values are set. When the outcome is minimalistic and unambiguous, it is easier to determine whether or not there is danger of loops or if the state controls cover all of the possible failure situations. A simple and well-organized structure is also easier to debug online.

3.4 Safety aspects of the software project management

The software project management refers to methods required in organizing software projects and concerns the overall software safety. This aspect of safety does not relate to the actual safety functions implemented with software, but the safety achieved by properly organizing the software project. (Schäuffele et al. 2013)

Basic safety thinking in the software process itself includes:

- documenting (to be done throughout the project),
- software architecture planning,
- coding rules / management,
- software versioning,
- testing, and
- validation.

Documenting the process is vitally important. Proper documenting and access to the documents ensures the flow of information within the team or teams. In regard to software, the output from the previous processes were used as the input for the software process, thus a carefully planned logical and technical structure are the foundation of the software development process. The software architecture and planning is explained more in detail in section 3.5. The section also describes the programming rules that were created after software architecture plan was agreed upon.

One extremely important factor is software versioning. It is the key to keeping the programming process in order. When a software function is complete, it is subjected to testing. If the performed tests approve that the functionality is as specified, that it is safe (no risk of deadlocks) and that the module fulfills its task, it is marked as verified. The compiled stable versions, especially the release or boot versions, should only include verified software modules and vice versa, and the test versions should be marked

accordingly and only be used temporarily. This is because any thoughtless changes in the software can result in unexpected and unknown behavior. (Kasurinen 2013)

Thoughtful planning can reduce the amount of resources this phase consumes. The process of testing and verification is required for each module that has been changed and sometimes for modules the changed module may affect. In a well-planned architecture, the verified software modules will not usually require any fundamental changes. In order to minimize the risks, the release software version should have only validated modules. Versioning will keep track of the development versions of the modules, indicating whether it is a beta, verified or validated version. It is also good practice to maintain a version history for each module. (Kai 2010, 217) (Schäuffele et al. 2013)

If problems should be detected in use, the relevant versions should be marked with some kind of identifier and determine a priority class for the fixing required. This ensures that a stable version may be compiled anytime without the risk of including old and possibly faulty code.

3.5 Software architecture

It is vital to create a software architecture plan that allows combining all the necessary logical operations and keeping the internal communication and control programs simple and straightforward. The IEC 61508-3 annex A expresses recommendations for software development according to the identified risk classes. It would have required more resources to create fully compliant software, so it was mainly consulted for guidance while planning the software. Semi-formal methods were used to document the requirements. The chosen requirements were modelled as function blocks and their interconnections were planned. The functions related to torque control were assessed as SIL2, which largely dictated the technical requirements for the software architecture. According to Pressman, the design process begins with data, architecture and interface designs, and then proceeds to procedural design, which is related more closely to the logical system architecture design (Pressman 2001, 423).

It was decided that the data structures of the modules will keep their own internal structures, and the requirement for global level variables is minimized to keep the variable accessing in control. A global registry was chosen for collecting the data from the top level software modules. A collective data structure was chosen because it could be easily sent to the other PLC or another device for debugging purposes. The data structure was

divided into categories, for example to a sublevel for input and output signals, to further mimic the situation where the modules may be independent equipment with their own inputs and outputs. Thus it was important to make a clear decision which levels of modules or function blocks have the rights to write the information to this global registry. Logically, the top level module that is calling its submodules, writes the inputs and observes the outputs of the submodules, while all the relevant information from this top level module is made accessible for the other top level modules through the global registry. However, between the layers the input and output system would be preferred between the layers because of the principle of information hiding. This is a common programming principle meaning the module interfaces are designed in a way, that only the data absolutely necessary is given through the outputs (Pressman 2001). According to Pressman, the greatest benefits are provided in the software editing and testing procedures. Some regularly required internal values, for example the state of charge read over BMS CAN, could be written as submodule outputs, but the practice was omitted. Instead, the submodule is writing all the information received over CAN bus to a specific global data structure. Similarly, it is also typical in automotive control units that the unit sends a great variety of data over CAN and the data is available to all other control units in the network.

The foundation of the software architecture was laid out as individual modules that in real life would most likely be implemented as independent controllers. Each is implemented as their own independent program. The module interactions, and their interfaces, are designed in a similar fashion. Some of the modules can operate on a run-signal without any other input signals and on a higher level, the status may be followed either by checking the state of the module or its status outputs. The hierarchy is carefully planned with as much exclusivity as possible, preventing random write access to variables and parallel or conflicting control commands. It was also noted that this way the program could be run sequentially and the use of software semaphores could be avoided. A simplified module hierarchy of the VECU and HCU can be seen in the Figure 10.

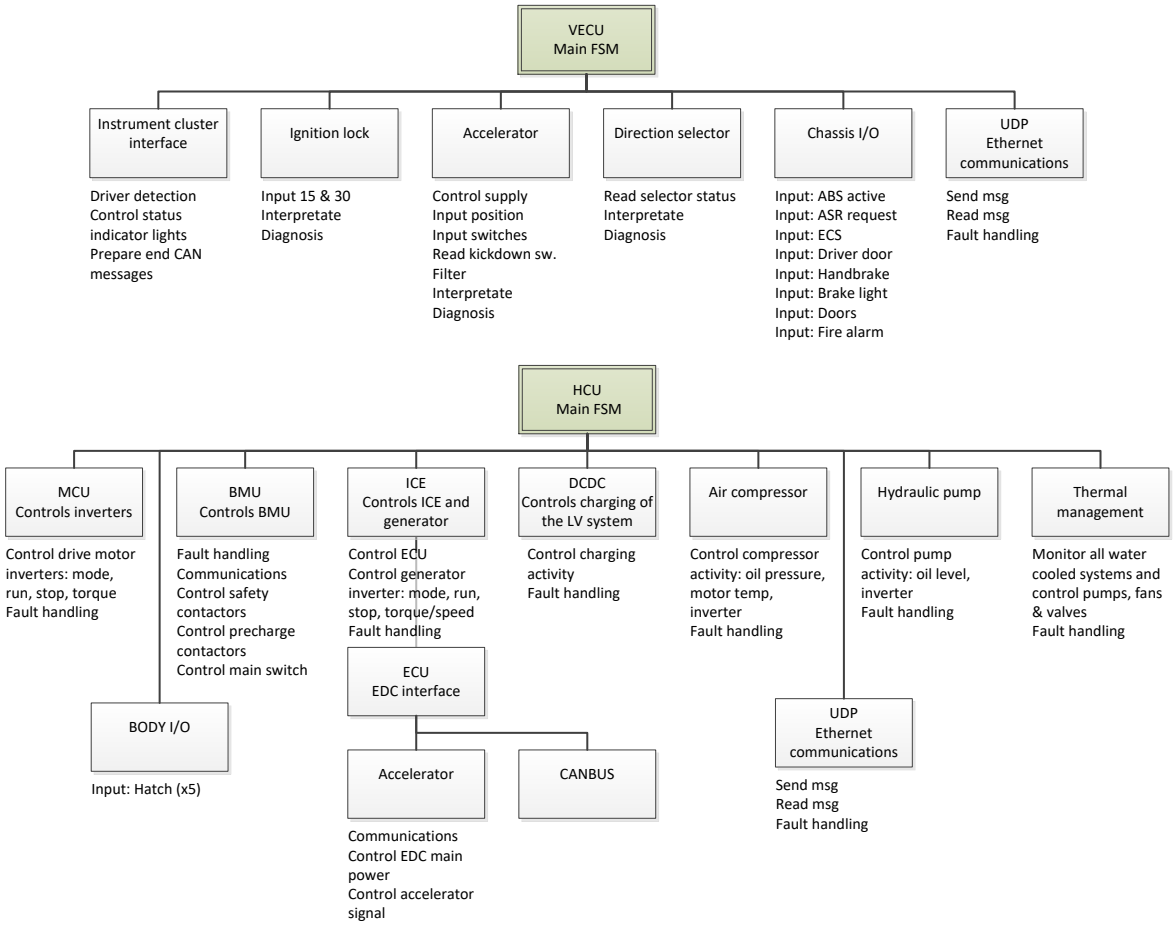

Figure 10. Simplified software module topologies of VECU and HCU. The functionality of the sub-controllers (gray boxes) is implemented using individual functions with straightforward internal structure.

Depending on the task scheduling, one may be able to avoid using semaphores. In this case, a cyclic running method was preferred. A multitasking environment with multiple task priorities and the use of events would require the use of semaphores, but we decided to run the whole program in a sequence with a short time interval and to use input polling instead, so there was no need for semaphores.

All the user interface button and switch interpretation was done by associated finite state machines (FSM) to ensure proper filtering and that the selections are made in a specified order to prevent accidental selection. For example, some switches might be activated before turning the ignition key, which acts as a master switch to many functions, and some functions might be activated unwillingly. Using edge triggers and state machines will help avoid the awkward situations in cases where the interface command buttons are not working as expected. To further advance the input handling, there should be another route

for the signal through a diagnostic system that evaluates the plausibility of each signal. This is discussed in a bit more detail in section 3.6.

When beginning to translate the design models into operational software, one must carefully think through the procedures and requirements for loops and all dynamic behavior in the software. The embedded software safety requires that the software is implemented in a way that there are no possibilities for a deadlock. There should be no dependencies that make the software wait for something; instead, each required input or process state is evaluated against a timeout clock and a failing process is then dealt with using the rules derived from the logical system architecture. Furthermore, it is also an IEC 61508 recommendation to avoid dynamic structures (objects) in a safety critical system (SFS-EN 61508-3 2011). The creation of dynamic objects and allocating memory during the operation could lead to memory leaks or resource pre-emption, which in turn could lead to unexpected results. Some dynamic behavior may also affect the processing times and cause timing problems for the more critical processes. When the software is designed as straightforward as possible and all the code can be run at each cycle with adequate remaining processor time, it is ensured that there will be no resource conflicts or deadlocks. (Pressman 2001)

The software algorithms must be well documented so that adequate testing, and later development, is possible. In this case, the algorithms were first tested in the MATLAB/Simulink environment with relevant simulations before being testing in the real environment.

3.6 Monitoring functions and diagnostics

The monitoring and diagnostic functions are the basis for both safety and reliability of the control system. Their purpose is to ensure the safe control of the equipment at all times, even after a failure. Obviously, it is important to provide first a safe technical solution, as already mentioned in section 3.2. Some solutions cannot be made safe or reliable enough by means of mechanical design and in some cases, a higher level of safety or reliability through mechanical design would not be cost-efficient. (Schäuffele et al. 2013)

The overall risk may be decreased by embedding software safety functions. In contrast, a poor software design or careless implementation is a risk in itself. To reduce the risks, software planning must utilize a sensible, predefined scheme that all the participants agree to follow. Software safety must also consider the hardware and the possible

problems therein, especially in the safety-critical systems with diagnostic capable hardware. (Schäuffele et al. 2013, 212)

It was decided that all the software modules would have their own means of detecting safety issues, most of which rely on the equipment manufacturers' own management and control systems. Thus, the main requirement is to monitor the equipment status and handle the fault situations. In a vehicle, it is usually sensible to try recovering the functionality before entering a fail-reduced or fail-safe state. Thus, less serious equipment failures would at least allow the driver to maneuver the vehicle into a safe spot.

All the software related to external communications is equipped with several methods of safety. The communication layer itself is covered by the hardware and relevant software libraries provided by ABB. For instance, all used communication paths use CRC32 or CRC16 checksum to verify the received packages, they monitor the transmission intervals to detect a communication timeout, and include additional functionality that will require the critical commands to reset to a safe state before allowing the system to resume. In this system, for example, the module level operation is relatively simple except for the diesel generator combination. However, considering the multiple failure possibilities, the software must be able to carry all the necessary information to the highest level of the system so that it can either reduce or stop operation of a particular module, or command a reset if permitted. Establishing a comprehensive fault-handling logic requires meticulous assessment of the possible fault situations and their combinations. Naturally, the most important software prerequisite is that there are adequate means, for example input signals, for detecting faults. The detection routines and fault-handling logic must be tested in real-world situations and the control software must bring the system to the predefined safe state if necessary.

An additional isolation-measuring device was also specified. When it detects a significant reduction in the isolation resistance (e.g. in case of short-circuit of one individual AC phase), the driver is warned and the vehicle is allowed to continue driving in a reduced mode until shutdown. A new start is not permitted if an isolation fault is still detected.

4 THE TESTING PROCESS

This chapter will expand on the testing methods and process used. The foundation for the software testing process was simplified from the ISO/IEC 29119 and IEC 61508-3 suggested practices. As this project had only minimal human resources, there was no possibility to create a separate testing organization. To avoid the ethical problems and minimize the psychological aspects of a programmer testing his own code, an independent testing organization should always be set up. With the minimal resources available the test organization is in many cases the person that has created the code, which is a highly susceptible method because of a higher possibility of blindness for the mistakes. A separate test organization would be more objective, but the organization also needs guidelines for the testing. (Kasurinen 2013)

Because of limited resources, the project's management decided that automated testing would not be implemented. The software testing was thus done separately for the code, which was already run in trials and performing in real-life situations. A formal report was written for each test and its results. Due to the limited scope of this work, only a selected base version was tested. The critical problems were corrected and the relevant modules were re-tested accordingly. Other corrections and relevant testing would be done later on according to the produced test reports. After corrections or additions, the software must undergo all the testing procedures. Sometimes a small fix is required during use, but in principle all the changes should start from the design process and thus be documented at each level, and then tested and validated in the end.

The software architecture map describing the modules and their dependencies are listed. Each module must have a written description of its functionality. A structural inspection of the code is performed. The first check will ensure that the commenting is uniform and the module version numbering is up-to-date. If the functionality of the module is not obvious from the written description, the modules must have a flow chart describing the process in more detail. The software written in graphical continuous function chart (CFC) language is easy to understand and debug. Some examples can be seen in section 5.3.3. In this project, most of the code is written in structured text (ST) or CFC. The program code, clearly stating its version, has to be included with the module information package. Then the inputs and outputs are listed and all cases of their expected behavior are listed. From here the test cases can be formulated. Each signal should have random noise applied to create unexpected behavior as well.

4.1 Software test principles

The software tests must relate to the specified design requirements. In more formal development, the test case can thus be planned early in the process. According to Pressman, the Pareto principle is applicable, which means that it is common to find most of the errors in a certain small part of the software. The testing process begins from modules to the higher level software which manages the individual modules. To prevent the ethical problems and to be more effective, testing should be performed by another organization, possibly a third party organization.

The first principle of testing is to check the operability of the modules. The modules must work flawlessly without bugs that would preventing running the code. The second principle deals with the observability. The code must be easy to debug, the source code must naturally be available, and all the states and internal variable processing, and the input and output processing must be easy to interpret and observe. The third principle is controllability, which addresses combinations of inputs and outputs, their interdependencies and functional predictability. The fourth principle deals with the decomposability, which looks at the modular design of the software. This leads to the principle of the simplicity of the code: the simpler the software is, the easier it is to test and obviously the less it is prone to bugs. The next principle is testability, which looks at the structural simplicity. The last principles deal with the stability of the software, its error handling capabilities and stable operation, and the tester's ability to understand the documentation and information. (Pressman 2001, 439)

4.2 Software test methods

The software module tests were done using white and black box methods in a simulation environment. During the integration tests the handling of erratic real-life signals will be verified. This is done by either interfering with the physical signals or the software by adding an interference created by the pseudorandom binary sequence method, or both. After this phase, the testing of the highest level control system must be performed.

The functional testing of the modules, and their relevant control structures and sequence controls, mainly consists of checking the normal expected operation and the induction of abnormal input values, and verifying the fault handling. The abnormal input values must correspond to the expected failure cases in those modules that include fault handling. A test plan is made to cover all the preconditions, expected results and postconditions.

Sequential operation is tested likewise with attention paid to the expected events at the inputs and the cases of unexpected operation representing malfunctioning inputs. The functional test plan is written down in checklist form to ease the testing process and must include the following scenarios.

The code is to be observed for obvious bugs, for example variable type mismatches and loops. For this purpose, values out of range are induced (e.g. of wrong types of variables), to see how the component can handle the situation. The next step would be the boundary value analysis. In this check, the input values are given from both sides of the borders of the permitted range. This will address the software configured limits and scaling, and the internal data structures (e.g. arrays), which have to be checked at their boundaries. In this case, the software does not have any dynamic arrays or loops, so this is relevant only regarding the inputs and outputs, and the relevant internal calculations. (Pressman 2001)

The logical functionality must be tested with all the expected combinations. To test the logical functionality in unexpected fault situations, the tester intervenes in the operation of the system by forcing the internal values and signals in the programming environment. This ensures that the coordination of the integrated equipment is tested. This is done by verifying the expected behavior of the components with all the input and output combinations. This also correlates to the possible signal diagnostics implemented in the module, and correct functionality of the diagnostics can be verified. It requires proper planning of the test cases to test the diagnostic functions in a simulation environment using noise generators or other means to interfere with the signals. The input value testing correlates to the missing input signals (e.g. open circuit or short to 0VDC). Some of the digital inputs might have an algorithm to discover erratic signal behavior, and some of the analog inputs have model-based behavior or other methods to monitor signal quality. The diagnostic functions may also react to constant high signals (e.g. short to >10VDC), or static signals within the permissible range.

Although it was not done here, each module could be monitored for the processor cycles it needs to finish in different operating conditions. This could be documented with the other test results and may help to determine if some parts of the software require excessive processor time, possibly causing problems after the system integration. The overall process timing was checked with Codesys task monitoring.

4.3 Module testing

This phase of testing correlates to the technical system architecture plan. Its aim is to verify that the technical implementation of each unit or module works according to the plan (Schäuffele et al. 2013). All the measured values are checked and the operation is thoroughly verified. Fault handling and entering the fail-safe state must be tested in all of the internal states of the module. Depending on the type of the error, the module must either recover or enter the fail-safe state permanently.

A thorough testing of some of the modules would require simultaneous operation of other modules. For example, it was not possible to test the diesel engine with a controlled load before the whole powertrain was installed in the vehicle, so only the basic functionality of each module was tested individually and the mutual operation controlled by the higher-level software would be tested during the integration tests.

4.4 Integration tests

The aim of this phase is to integrate and verify the cooperation between all the completed and tested modules. During the process, all the electrical connections and schematics are checked and revised, if necessary. It is quite common that some minor changes are made and they are not instantly documented. In this case, everything was checked through and the input and output systems were tested.

The checking of the overall timing correlates to the hardware load of the CPU. The hardware processing capacity is tested by applying full load with all the possible features active. The Codesys cycle time monitor was used to determine whether the hardware load stays at a safe level, meaning that the processes have an adequate time window to complete and the processes do not overlap and cause priority and other timing problems.

A list of activities and tests that would cover all the normal operation, and a description of sequences required for the testing was compiled. Another checklist was made to deal with the most likely failures, which would be tried in order to see whether the higher-level control is able to cope with the failure situations of subordinate modules.

As the modules may or may not be able to reset and deal with the errors, the higher-level controller must be able to wait for it to recover or enter the final fail-safe state. The higher-level controller must also be prepared in a way that its operation is not fully dependent on the internal states of the modules; it mainly manages them. This was tested by causing

the modules to enter a fail-reduced or fail-safe state in all possible states of the higher control. The most obvious dependencies relate to the possible inability of BMS to provide power for the consumers.

The integration tests require verification of the cable connections and a successful configuration and I/O signals test. The testing of the actual functionality of the physical equipment is a part of behavioral and system testing. If all the tests of the logical system are approved, the vehicle must make real-life test cycles during which the control parameters are properly calibrated initially and the system is stress tested. As explained in the scope of this work, these tests are only being initially planned because the time allocated to this project is inadequate. This test should prove that all the user requirements have been met, for example, the diesel engine does not overheat and the vehicle can be operated safely also in the freezing winter conditions. Thus these tests cover also the design and capacity of the cooling system, which was already planned before this control system project.

4.5 Validation tests and commissioning

An important part of the validation test and commissioning is the vehicle inspection required for the registration. However, this will not confirm the proper fulfillment of the other user requirements. The other user requirements are checked according to a plan constructed to cover all the requirements and specifications. The commissioning test must include a plan to cover all the normal use and reasonably expected misuse, including the triggering of fault situations to verify that they will be handled as expected. As the goal of this project was merely to create the control system, the calibration of the systems and the commissioning test go beyond the scope of this work.

Methods for testing basic functionality was documented and executed. For example, the later stress tests will disclose whether the cooling system is adequate and does not cause heat-related issues in other systems, or whether all electrical connections can withstand the harsh conditions they face in everyday driving conditions throughout the year. From the control software point of view, the methods of handling these extreme situations must be tested in real-life stress test situations. These parts of the software were not fully ready so it was not possible to test the software module or integration.

5 RESULTS

The software environment with the basic functional requirements was completed at the end of the project and the vehicle was subject to official inspection and registration. Many features of the logical system plan were omitted, but the vehicle fulfilled the legal requirements, and from this point road testing would be allowed. Measurements related to energy consumption should be carried out to optimize the system and provide research data to validate the simulation model parameters. New software features are also required. The planning required to properly implement these features should be organized in a manner that the modularity is preserved, and unnecessary, laborious iteration rounds are avoided. The software architecture was successfully planned in a modular way and it proved to be easy to add mode internal modules according to the rules agreed upon.

The documentation processes produced a number of manuals and other documents. These include the original plans, flow and brainstorming charts, user manual with service and troubleshooting tips. There is also documentation about the risk assessment strategy and the assessment tables, as well as the test strategy and test results. While the risk reduction process produced specifications and design features, some were executed as instructions for use.

The ALARP in the risk processes was determined loosely to lower the probability of risk to negligible or rare, and the possibility of avoiding the event was determined as likely or possible. The reassessment verified that the system design requirements could match the level required by the ALARP process. This concludes that even the SIL2 classified functions have been addressed seriously during the development and it is highly unlikely that they would be the cause of an accident. There is at least the possibility that the driver is always able to intervene and prevent the accident by taking corrective actions.

5.1 Results of the software process

The logical architecture and software functionality were sketched as flow charts and state diagrams for all the relevant functions. This helped to understand the possible problems in module interaction. Also the actual programming benefits from a well-made plan. When the code is divided into tangible blocks, or modules, and the programmers obey the plan, the risk for dramatic programming errors is reduced. A well-documented plan is crucial also in the testing phase. Some examples of these charts and diagrams were already

used in the text to help understand the described process. An overview of the actual software module names and their call tree relationships can be seen in Appendix II.

Because the focus of the project was somewhat scattered in the beginning, some of the plans were actually made later in the project. This mostly happened because of the pressure to integrate the system before fully understanding all the equipment and that the vehicle was supposed be in driving condition before any of the module tests were fully executed and completed. The earliest prototype code used ladder structures, but later on they were mostly converted to ST or CFC code. Because of the complex functionality required in the system, and the limitations of the ladder implementation, this change made the further developing more manageable.

Each software component has the basic information commented in the header. All the documented test results combine this with the design charts, and list the test cases and their results. The result form also must include the version identifier as well as the date and time of the test. Some space for free commenting of the component functionality was also reserved on the test result form. This was used to write down ideas for further development or other suggestions.

As mentioned already in the software testing, the CPU load and process timing were checked with the CPU cycle time monitoring of Codesys. The processing capabilities were adequate and the hardware load acceptable. The HCU unit has a more powerful CPU, and even after adding a rather complex anti-slip algorithm there were no cycle time issues.

Even though the software process did not always proceed as planned, the software was surprisingly bug-free. Most of the problems noticed were some minor mistakes caused by negligence, creating critical issues mainly when related to variable type mismatches. Other problems were usually related to poor initial planning, resulting sometimes in a completely rewritten module code. The reason why there was a relatively small amount of errors was probably because the code was actively tested in real-life situations, where the bugs would be noticed and fixed instantly. Because the vehicle was tested in a closed environment, this practice was not seen too risky. One conclusion of the testing process was a suggestion to develop variable naming conventions to include the type of the variable. This would help both the programmers and the testers. An example of a test report can be found from Appendix III.

5.2 Validation and real-life tests

The validation test procedures were designed to compare the resulting software with the logical system architecture, in order to verify functionality versus specifications. Additionally, the commissioning tests should include prolonged stress testing with full load in the worst-case scenarios, for example, driving in extreme weather conditions and harsh road conditions, and testing the isolation monitoring in rapidly changing ambient conditions. This, however, was not possible to arrange during this project. The author would still suggest committing the bus to such tests to see any design flaws that may not have been thought of. This would also benefit future projects.

If all the pre-defined safety, legal and user requirements have been met successfully, and the vehicle has passed the test processes, the project is considered completed and the resulting product is validated against the design requirements. Because of the nature of this research vehicle, new user requirements will arise during the use, and thus to keep the vehicle safe for public use, the iterative development processes must always follow the systematic approach laid out by this project.

Most of the equipment was pre-chosen and to verify the adequacy of their specifications in prolonged stress tests is yet to be seen. This mostly concerns the calibration and use limits set in the software.

5.3 Case example: The accelerator

This section explains the practical implementation of the accelerator system. The accelerator was chosen because it represents one of the most critical user interface and control elements. The electric brake, or regeneration control lever, uses essentially the same program as the accelerator, so the described diagnostic procedures and operational logic work in a similar fashion. The analysis of the design requirements is described first, after which the functional requirements and safety aspects are observed. The later part of this section will present the software implementation itself and the diagnostic features implemented therein. The overall results of the software processes will be presented in section 5.1, therefore the results for the accelerator testing is not be presented here in detail.

5.3.1 Accelerator design requirements

The accelerator pedal has very simple functionality from the driver's point of view. The pedal acts as a wish pedal, its output commonly referred to as "the driver request" in automotive literature. Depending on the engine management system or motor control, the output request value may be torque or fuel quantity or in some cases rotational speed (Reif et al. 2014, 669). The HCU drive control system was designed to work as a torque controller so that the VECU provides a torque request value depending on the driving conditions and the driver input.

The accelerator pedal of the CAMBUS vehicle is an older VDO E-GAS potentiometer implementation providing an analog voltage signal of the pedal position and a electromechanical safety switch signal, sometimes referred to as an idle position switch (VDO 1996). The risk assessment concluded that a straightforward implementation would introduce a very high risk. However, the team determined that this accelerator system is able to fulfil the safety requirements after implementing a proper software safety strategy, thus meeting the requirements of the risk reduction strategy. Figure 11 shows a brainstorming diagram of the main topics related to the design requirements.

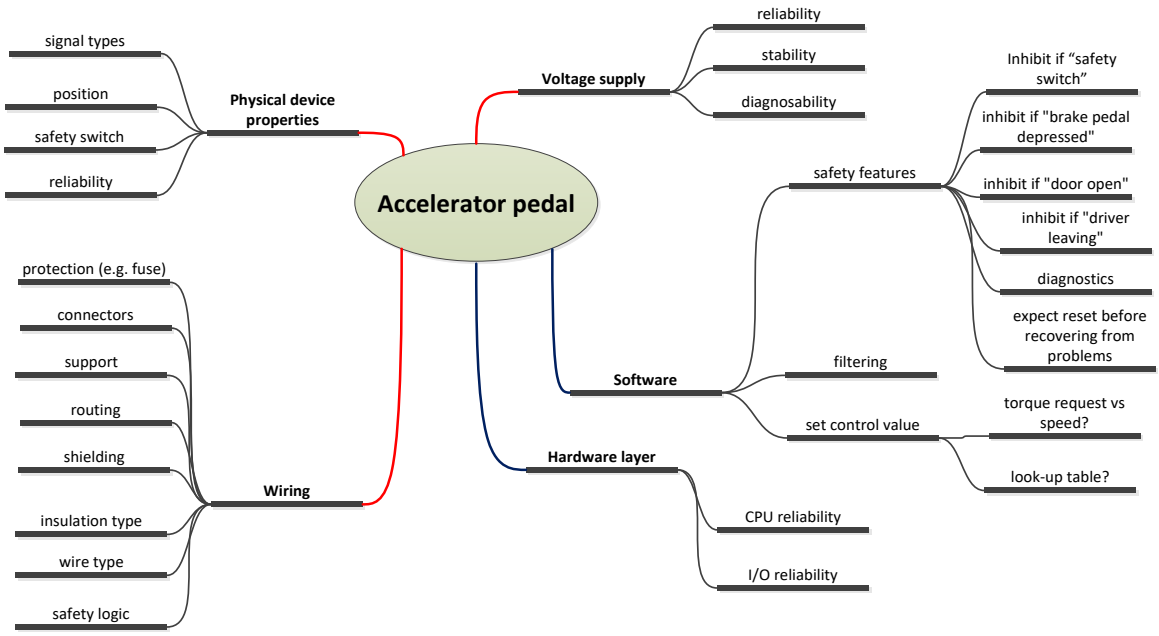

Figure 11. A brainstorming diagram of identified factors related to the accelerator pedal.

Each of the subtopics in the brainstorming diagram would include detailed analysis and criteria. For example, the connected equipment and cable locations determine the

requirements for heat and chemical resistance and the electrical specifications for the individual cables. This work would mainly consider the topics relevant in the software design and implementation.

5.3.2 Functional safety requirements for the accelerator

The chosen technical architecture provides the PLC I/O and hardware processing, as well as some diagnostic features, but the main diagnostic functionality provides several tests within the software.

The VDO accelerator pedal has a static resistance in series with a potentiometer, which together produce a known voltage range for a healthy output signal. Thus, the VECU software proceeds first with a signal range check. The second check considers the correct operation of the safety switch, comparing its state against the fault-free position signal to determine whether the switch signal is plausible. The potentiometer signal has slight variations constantly, so one check is monitoring for a static signal. The quality of the analog signal is verified with a dual linearization and slope comparison, which detects excessive noise and severe signal jumps. A check for the potentiometer supply voltage was also designed.

The faults are prioritized according to the risks involved. Some of the detected failures are first flagged temporary and the system is allowed to reset them a number of times (fail-operational). The resetting of an intermittent failure was implemented by counting the amount of fault-free cycles. If the failure is detected repeatedly or is otherwise persistent, the fault flag is marked permanent and the accelerator functionality is either reduced or disabled. After an accelerator related fault is cleared, the pedal is expected to be fully released before accepting new input values, as described before.

There are multiple communication pathways, which are expected to work flawlessly. Communication is checked constantly and critical input values are reset to zero if a communication error or timeout is detected. If the problem is cleared, the receiving unit will require the physical pedal input to reset as described before. The data flow and the accelerator functionality are demonstrated in a simplified manner in Figure 12.

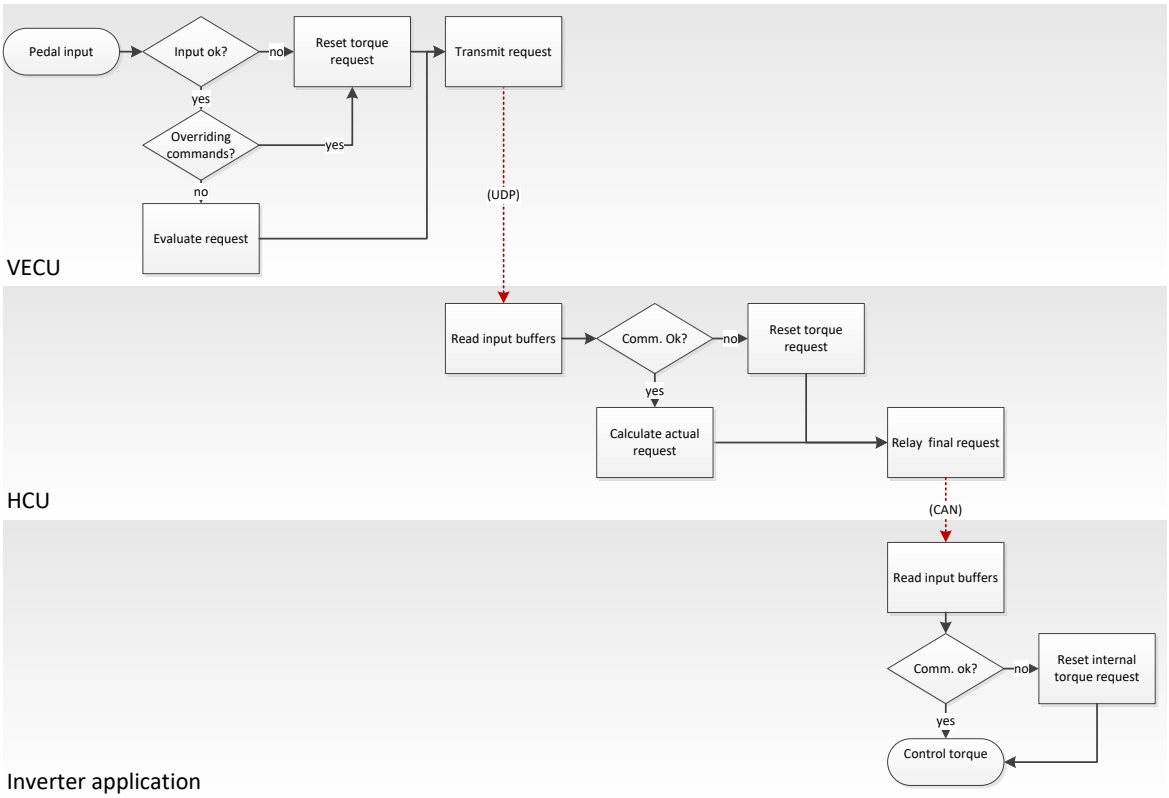

Figure 12. Simplified command path of the accelerator, including two communication links. The red dotted lines represent communication over an external link. Each related step is evaluating the request coming from the higher level, whether it is reliable or not, and resetting the request in case a problem is detected.

The accelerator request is evaluated only if the pedal's internal safety switch is enabled by depressing the pedal. Thus an accelerator failure of this kind would require two simultaneous failures of the pedal system. The communication path errors would cause immediate resetting of the accelerator request (within 20ms) and resuming requires a zero-position resetting of a faultless system. The final stage of the safety chain is the inverter software, which in an emergency can only be controlled by the stop signal mentioned before. However, an inverter user application was designed to require similar resetting of the input request to maximise the safety and to prevent powertrain jolts.

5.3.3 Software implementation of the accelerator

The main accelerator software unit consists of an I/O handler, a logic that determines if a torque request is permitted, and a unit that determines how much torque should be requested. The I/O units first read the pedal related inputs and filter the signals. It also

includes a separate path for the signals to pass a series of diagnostic tests. The block will then generate filtered output signals and the current fault status. The following figures will demonstrate the accelerator functionality written in the graphical continuous flow chart or CFC language of the IEC 61131-3. The first accelerator program block can be seen in Figure 13.

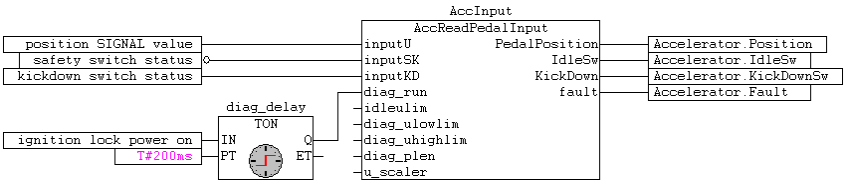

Figure 13. A simplified presentation of the accelerator input handler. The diagnostic run command is given after a delay, after the voltage from the ignition lock switch is detected to ensure that the system is in normal state (i.e. there are adequate supply and input signals available).

Parallel to this, there is a block that controls all the safety related conditions of the accelerator. The accelerator idle or safety switch, and the brake pedal switch, are treated as the most important driving related interface safety features. The communication pathway error handling is also considered one of the highest level safety features. Whenever a safety feature is activated, it will set a flag. Any of these conditions will reset the accelerator request in the next step. When all the safety conditions are reset, and the release of the accelerator pedal is detected, the flag is reset. To prevent a possible unwanted immobilisation of the vehicle in a failure of one or more of the second level safety features, there is an override button that can be used to re-enable the accelerator. This was done to allow the driver to forcedly move the vehicle from a possibly dangerous location where it has stalled otherwise. Figure 14 shows how the safety flag is being set and reset.

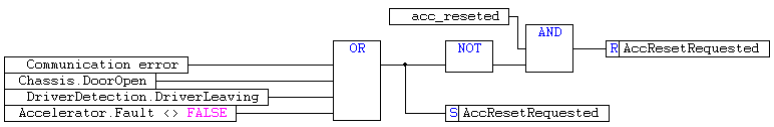

Figure 14. A simplified presentation of the accelerator reset functionality.

Figure 15 shows the actual conditions which set the enable flag for the accelerator. One of the control signals is the reset variable of the previous example.

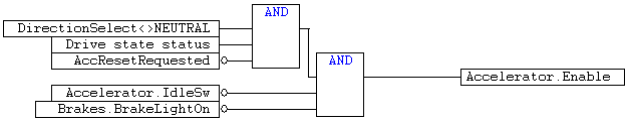

Figure 15. The enabling conditions of the accelerator functionality. The accelerator safety switch *(IdleSw)* and the brake pedal switch are considered to be of the highest priority, thus they always disable the operation of the accelerator pedal function.

The final step is to check whether the torque request is allowed and to calculate the torque request according to any given parameters, for example vehicle speed or traction motor temperature. The block, which is seen in Figure 16, may contain a look-up-table or calculate the correct request based on a model.

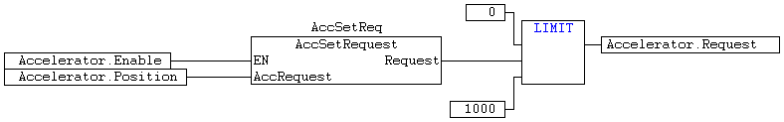

Figure 16. The final stage that determines the actual torque request to be sent to the HCU. All the other input parameters are omitted from the picture. When the *AccSetRequest* block input *enable* is FALSE, the output *Request* will automatically be reset to zero. Even though the *AccSetRequest* block already controls the *Request* value and is tested for handling possible illegal position values, an additional LIMIT function is used to prevent any out-of-bounds request values.

A similar method is used for the electrical brake control lever. The HCU has a voting function, which determines the final torque request value sent to the traction motor inverter, or the accelerator control signal of the diesel engine in the direct drive mode.

This functionality determines if a torque request from the accelerator or the electric brake control lever has been applied. If not, the system will check if the vehicle accelerates after the accelerator pedal has been released and activates a downhill brake control function to keep the vehicle velocity below the set value. The set value is registered at the moment of pedal release. If instead the speed is within the configured crawl speed limits, the system will apply a crawl torque. In addition to the crawl, a “hill hold control” is planned. In any other case, the vehicle is allowed to coast. A sensorless anti-slip algorithm tested first on an experimental vehicle was adapted to the bus control system to provide further research data and verify the operation of the algorithm (Montonen et al. 2014). If the slip control is

configured as active, the accelerator torque request must pass through the slip control module. Before the final stage, the torque request must also pass through the anti-jerk function. A presentation of the command path can be seen in Figure 17.

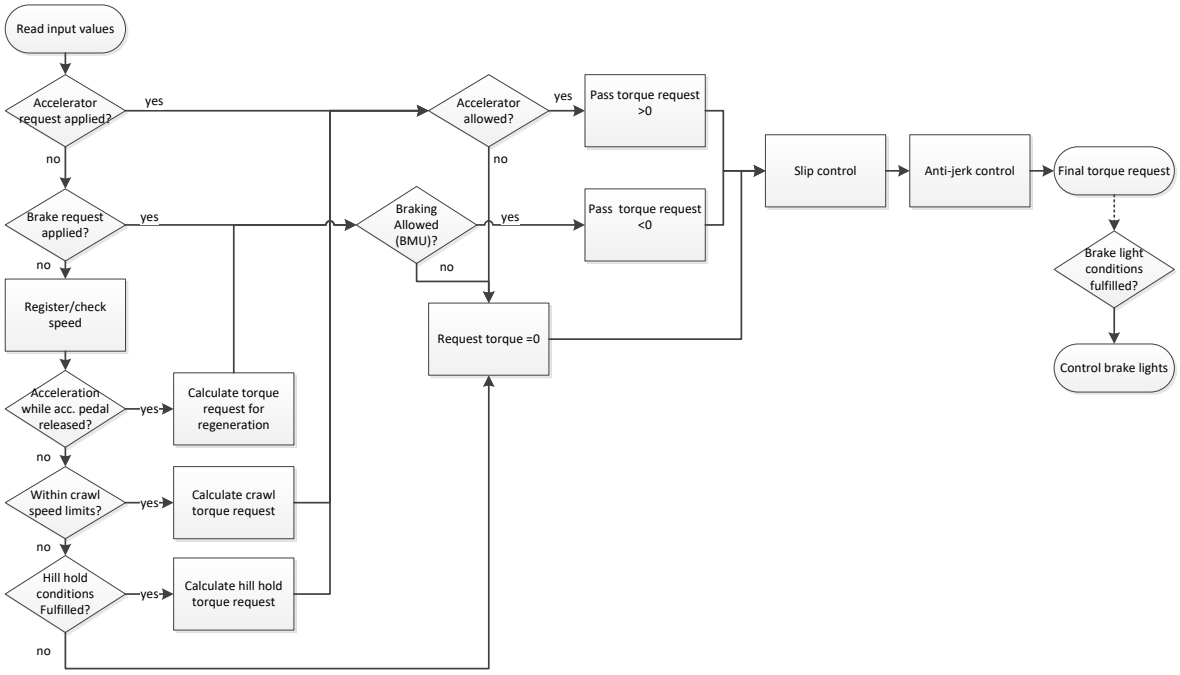

Figure 17. A flowchart demonstrating the principle operation of the final torque control system.

If electrical braking is requested, the torque control function will also request VECU to operate the brake light accordingly. Combining the electrical braking fluently with the operation of service brakes is complicated and in this case, it would require upgrading the old service brake system (Reif et al. 2014, 736). It would be too complicated to pursue within this project.

5.3.4 Accelerator fault diagnosis

The diagnostics must be able to reliably detect a failing accelerator pedal. The current setup utilizes the vehicle's original VDO pedal, which consists of only one film potentiometer, so the methods of the following paragraphs were designed in order to ensure the safe operation of the pedal.

The voltage for the potentiometer is supplied and regulated by a PLC analog output. The analog voltage signal is read by a PLC input module equipped with a 16-bit ADC providing

a value with a resolution of 0.4 mV. The program accesses the value every 10ms. To avoid glitches in the signal, the input signal for the driver request controller is passed through a median filter with a window size of five. Though the median filter will add delay to the actual driver request, it was considered not to adversely affect pedal response. The rates of change of the raw and filtered input signal values are checked. The quality of the input signal was done by comparing a linearized slope with sample-per-sample slope. The method was simple and proved to work effectively enough. With current parameters the system was constantly able to detect noise comparable to 80mV peak-to-peak white noise generated using a pseudorandom binary sequence (PRBS) algorithm.

The diagnostic rules check the unfiltered signal in 10ms intervals for:

- signal “too fast change” test (2-5 cycles, depending on the test type),
- signal static: 30 cycles (empirically set time limit),
- signal range check: too high, too low (from current value) 3 cycle,
- idle switch error: 3 cycles (empirically set time limit), and
- supply voltage error: 3 cycle.

Some of the example values have a three-cycle minimum because the problem has to be confirmed to avoid triggering by mistake. A correct value should be tested in real-life conditions. For example, with one failure the filtered request value could change from 0% to 100% in an instant, but because of the diagnostic functions, the value is not accepted and an error flag indicates a too rapid change of signal. Because of the mechanical safety switch involved, it would take two simultaneous failures and the proper behavior of the position signal to defeat the diagnostic functions, which is why it is highly unlikely that the accelerator pedal could cause an uncontrolled acceleration.

To assess the delays in the communication path with the information given by the equipment manufacturer, the communications block will provide a new value in average time of 4 ms, which is less than the 10 ms cycle time. The interval of sending UDP data packages is currently configured as 40 ms. The processing of the block input, assuming that the receive buffer is empty, would take a maximum of 10 ms. The powertrain CAN message refresh interval is 10 ms. The inverter torque request ramp-up has been configured as 0.1 s per 100%, and using the multiplier of four (400%) this would mean 400 ms for the request to build up linearly to the maximum value. The inverter’s internal processing time for the request is expected to be less than 10 ms. According to this reasoning, the time it would take for torque request to reach the maximum level would

take 470 ms and could be cancelled with a 10-50 ms delay. However, this question is a bit trickier, which is demonstrated further in the next section.

5.3.5 Accelerator safety

The communication links check that if no error is detected, the request may be relayed to the next link in the chain. The errors were divided in three classes: always resettable, limited count resettable and permanent failures. If a limited count resettable error reaches the maximum count, it is then flagged permanent. In this case, the vehicle is still able to move using crawl mode, which is controlled by selecting direction and releasing the brake pedal. Depending on the type of fault, a higher limited accelerator value could be used to move the vehicle if the accelerator pedal is depressed. It is to be remembered that there are risks concerning the accelerator pedal, but there are also risks related to the immobility of the vehicle.

Because almost all of the variables in this review are configurable, only a rough estimation is given to demonstrate the problems involved in the processing delays. Evaluating the test rules mentioned in section 5.3.4, we can determine that the greatest risk is with a static signal that stays within the accepted values. Basically the vehicle would be able to accelerate freely for 30 cycles. To calculate the time it would take to detect and cancel the torque request, the whole chain of events related to the implementation must be observed. The pedal filter delay is 50 ms because of the median filter. The UDP packages containing the request are sent in 40 ms intervals. The HCU is processing the request with an S-ramp function to prevent powertrain jerks, allowing the value to rise to maximum in 1180 ms. Then there is an average of 10 ms taken by the Visedo CANopen transfer delay. In the inverter we would also have to calculate the ramp-up time 400 ms. This example would equal to a 1280 ms delay to reach full torque, and the torque request would be reset to zero at 320 ms. Add again the transfer delays and ramp-downs.

To put this into perspective, the torque response of the engine was estimated in a Matlab simulation. Sufficient delays were added to closer represent the actual behavior of the motor. The equations from Bosch Automotive Handbook were used to calculate the vehicle movement by the requested propulsion power (Reif et al. 2014, 774-779). The initial delay is mimicking the filter delay and the ramp speed mentioned before is used. The transfer delays and processing time are simulated by the cancellation delay, which is here at 250 ms after beginning. Figure 18 demonstrates the change in the travelled distance when the cancellation method is changed. A slow resetting with ramp-down

would cause the vehicle to continue accelerating after the failure has been noticed. If we take the kinetic energy and deceleration of an empty bus into account, the vehicle would be able to move much more than the 0.1 meters, which was the required by the ECE-R100. Using the same cancelation time and removing only the ramp-down, the vehicle travel can be reduced dramatically.

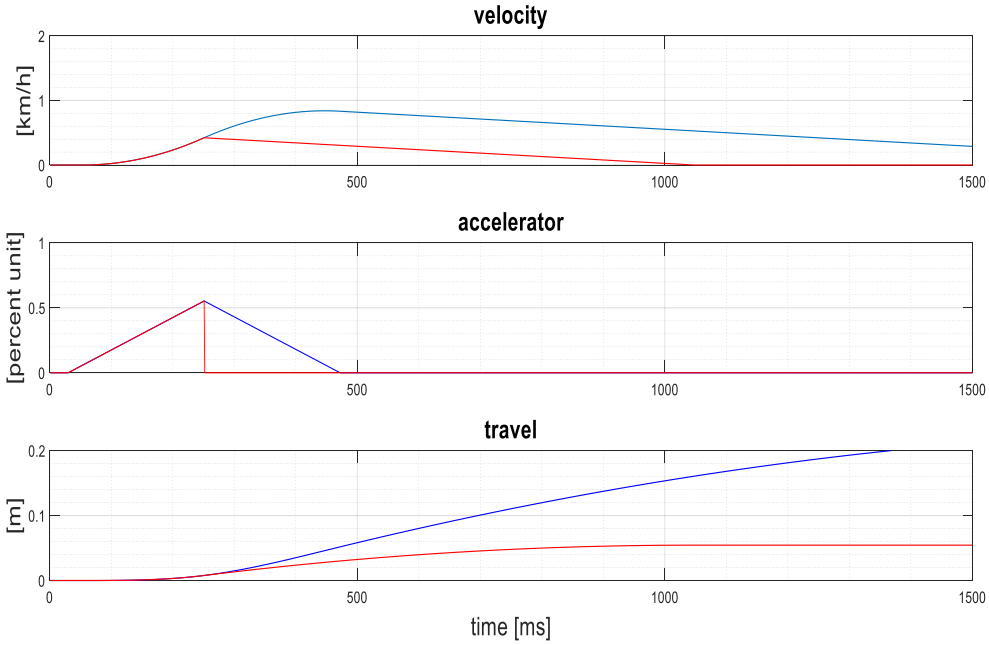

Figure 18. The simulation results represent the worst case vehicle acceleration from stand still during a 1500 ms time period. The accelerator request is cancelled at 250 ms. With the blue lines, the request value is using both ramp-up and ramp-down and with the red lines, immediate cancellation after fault is used instead.

From the figure we can see that even in the worst case of multi-failure of the pedal, with a proper cancellation method the empty vehicle would be allowed to only move slightly. This level of safety could be achieved, for example, by all the torque-control-related modules checking the actual fault status of the accelerator pedal and cancelling their operation immediately, and calibrating the diagnostic functions properly.

The actual tests proved that in order for the accelerator to provoke an out-of-control situation, a multi-failure situation should occur. This would mean both the safety switch and the potentiometer failing, and the input signal would have to pass all the software checks successfully. It is highly unlikely that this could happen in real life, so the assessed

residual risk of this implementation was determined acceptable. In case the monitoring application in the drive inverter is somehow not able to reset the inverter functionality, the driver still has the regular brake system and an emergency stop switch to disable the hybrid system.

In order to further enhance the system, the hardware should be upgraded first to support real dual processing and process monitoring. The algorithms can easily be applied to both of the inputs and the failing components can be voted out. This allows continued operation while the driver is warned to take the vehicle to service for a closer check-up.

Of course, in a real emergency, the other cancelling means would be used by the driver, but this review is done from the perspective of the worst case scenario per ECE-R100. The conditions were interpreted so that the driver must not interfere with the pedal error (UNECE 1997). In the case of a failing inverter, the failure may not be detected correctly by the inverter control system, in this case, the HCU control system must automatically send a stop signal to the inverter. It may not be possible to control any further problems, but if for some reason this would not be enough to stop the failing inverter, the driver still has an emergency button to stop and shutdown the system.

The signal test procedures involved an open-circuit or short-to-ground, short-to-plus and static signal tests, and an interference tolerance test by adding varied amplitude PRBS on top of the measured signal. The results of the tests concluded that with a single failure, the ECE-R100 requirements will be fulfilled. Even with two simultaneous problems the failures could be detected in most cases.

6 DISCUSSION

Trying to cover all the possible situations and add to the reliability of the system would easily become costly. In a prototype vehicle meant mainly for research purposes, the level of accepted risk is lower than in a bus meant for independent public use. In case a new prototype bus was built for public use, different kind of equipment should be used

At the end of this project, the powertrain control and optimization of the hybrid system is under development. Optimal changing and control of the hybrid modes has not yet been fully implemented or automated. The research on fuel efficiency will provide feedback for the mode optimization and algorithm design. This work succeeded, however, in providing a modular software platform for the future development.

6.1 Instrumentation

Good instrumentation proved to be a surprisingly difficult and time consuming task. The dash display should be able to present the vehicle status and a variety of messages for the driver. The messages may relate to faults or instructions directing the use the vehicle and some of them can be displayed with symbols. If it was possible, the symbols were selected amongst the ISO 7000 series.

Although the nature of the hybrid system is highly complex, the user interface, its visual outfit and presentation of the measured data and statuses, must be well thought. At a later stage of the project a fully programmable instrument cluster from Enovation Controls was acquired. While all the other CAN bus interfaces are predefined by their respective manufactures, a custom set of J1939 PGNs were defined in order to send all the required data to the instrument cluster. Right now the interface has the information required by the regulations, and some additions for the driver to cope with the fault situations. This is also a vitally important part of the safety plan. Special care must be taken that the user interface logic is uniform with the user manual and that the operators are noted of any important change. A commercial version of the instrumentation would require a thorough investigation of the user requirements, basically interviewing drivers experienced with EVs.

6.2 Safety aspects of the chosen equipment

The planning was not very effective in the beginning of the project. Some of the equipment features were not carefully planned, some of the features did not work as expected and some of the original equipment was not possible to investigate early enough in the project. This led to improvised wiring on site, sometimes even to a change of equipment or additions that were not planned originally.

Some of the preselected equipment did not fully conform to automotive design standards. This was accepted as the vehicle is a prototype after all and the non-conforming equipment can be replaced later, if necessary. Investigating these options would be a key issue for possible later development. Adding an accelerator unit with dedicated diagnostics and data bus communication should be considered. Looking at the system architecture again with the presented results in mind, relaying the information with shorter intervals would enhance the safety properties and simplify the software implementation.

A commercial vehicle requires a reliable electrical system. If this particular vehicle was in full-time commercial use, some of the existing cabling should be replaced. In addition to the regular electrical safety and voltage drop considerations with longer cables, an automotive design not only requires chemical resistance and a large-scale heat tolerance of the wire insulation, but also resistance to constant vibration and cable abrasion. Thus, a premanufactured harness would be beneficial. In harnesses, the wires are banded together, routed in conduits and placed in relevant cable supports to cancel the abrasive effects of vibration. The project provided basic schematics that could be used to create wiring harnesses for a retrofit vehicle. There is harness design software available to help select all the necessary components. Currently, when the vehicle itself is 3D modelled, the harnesses can be also routed and tried out in the model. A proper premeditation of the wiring also helps to minimize the EMI problems that may otherwise create problems with the control hardware as well. This should be considered in later developments.

6.3 Signal diagnostics

As all the input devices and their signals are subject to the possibility of a failure, care should be taken on how to assess the input values. Lack of time and resources prevented the use of more advanced methods, but they should be considered in the later revisions or projects.

It would be advisable to use a diagnostic capable input and output system instead of the digital inputs or outputs of the PLC, and diagnostic capable power sourcing. The digital input signals could be read as analog signals or assessed by a separate window comparator board. If, for example, all the signal states had known resistances, the signals may be subjected to similar tests introduced in section 4.1. However, the basic digital input system of the AC500 cannot reliably detect all the wiring failures. The inputs must be protected with current limiting resistors. The switch inputs should either have a pull-down resistor to ensure the input is driven to 0 volts when the switch is open, or to connect to the ground though the switch with a pull-up activating the input (Kai 2010, 126). One of the peripherals had a problem with unexpected intermittent triggering, but was not helped by a pull-down resistor, and was only cured after modifying the firmware and application filtering. Throughout the control system design, surge and load dump protection requirements must be observed.

In automotive actuators, the voltage can be fed directly from the battery via a fuse and the control unit pulls the voltage down. Nevertheless, the use of safe power sourcing can monitor the current consumption and shut down the source in case of overcurrent. In both cases the diagnostics can be implemented to the actuator by using current level triggering.

The author suggests the development of a more capable and comprehensive diagnostic system. In the beginning of the project, it was decided to completely omit the development of a diagnostic system, but the necessity of diagnostics was admitted later. Only a simple diagnostic system was designed to patch up critical safety issues. Now the implemented signal plausibility checks do not cover the detection of abnormally fluctuating digital signals. The author recommends making a separate input signal handling module, to filter and process the signals. It should include a diagnostic module that will be constantly observing input signal behavior. Each input variable should have an associated fault flag that can be triggered in case of a detected signal error, so that any erroneous signal could immediately cause the system to enter a safe state instead of potentially causing unwanted actuator behavior.

It is to remember that the amount of diagnostics, safety and reliability required must be determined by the risk assessment. The use of correctly rated equipment helps to lower the costs involved, especially in production series.

6.4 Traction-motor-related problems

Even though software and hardware safety was ensured to cover all the thinkable conditions, the chance that some equipment will fail and start acting erroneously still persists. There was one good example of this during the test drives. When traveling at a higher velocity requiring a field weakening operation of the PMSM motor, the control software was correctly requesting zero torque from the traction motor inverters, but the master inverter continued to apply torque. The problem was intermittent and could easily be defeated by using the service brakes.

The operation of the traction motor inverter is possible to cancel using the stop signal applied by a software component comparing the requested and applied torqued, or by an emergency switch applicable by the driver. However, this might lead to another dangerous situation as the voltage generated by the rotating PMSM motor will rise after the inverters stop modulating. If in turn, the battery was disconnected from the circuit for whatever reason, this would ultimately lead to a situation where the PMSM motor induces a very high voltage, possibly damaging or destroying the inverters or other equipment not being able to withstand the possibly high voltage. An automatic brake resistor is also installed, but the location of the resistor poses another threat. The resistor unit is installed in a sealed compartment made out of plywood with no ventilation to open air.

In a serious, life threatening situation, risking the equipment would be acceptable, as long as the physical design of the equipment ensures that all the devices connected to the HV can cause no additional danger, and that the insulation of the HV system tolerates high enough voltages. Relocation of the brake resistor is advised because of the risk of fire involved.

Although the driver is likely to notice any awkward behavior of the vehicle control system, it is also important to give the driver an adequate warning of any detected dangerous situation. The legal requirements demand that the driver is always able to use at least the service brake to slow down and bring the vehicle to stop safely. The reason for this particular problem was not fully confirmed, but could have been caused partly by a misconfiguration of the resolver zero angle on the master inverter or an inverter software bug. As the symptom is more or less intermittent, it will take time to find out the actual cause of the problem.

6.5 Project management issues

When creating something completely new, it is common to just take some parts and equipment, improvise and “just start building”. After a great idea, even if the equipment and its functions seem to fully exist in one’s mind already, one needs to decide how to go about prototyping it. At that point, a more or less abstract logical plan depicting the functionality is made. Then the technical or physical plan must be created, telling how the logical conditions are matched. These stages may be detected in just about any everyday building process, when analyzed thoroughly. In any case, even primitive plans are required in building a prototype or a product.

While the design processes themselves are iterative, many levels of iteration over the process and project cycles can also be seen. Many times people refer to the iterative nature of a specific development process, but iteration also happens between the completed product models, when newer developments further enhance the features of the previous models. In addition, prototyping processes may have changed or advanced. There is a significant amount of scientific knowledge available today; one can plan theoretically and model the system before starting to build it.

The author wants to bring attention to the fact that a loose higher-level logical or functional planning of the equipment can be done any time, even at the beginning of a project. Even if the equipment does not work yet, the equipment is in development or the equipment has not been chosen. It is the technical architecture phase that must select the technical solutions, and the module development phase that must enable the equipment to work as it was designed to work in the beginning. The problems should only cause a part of the project to slow down, and minor problems should not have any effect on higher-level management.

It was sometimes confusing to discuss the project management-related issues. The same people had to work with the lower-level modules, trying to get the technical features to work, and they would plan the higher-level system controlling the modules as well. Some of them worked with other projects and did not have full-time knowledge of what was going on in the vehicle building in the workshop. Many times the module level progress was slowed down by unexpected technical problems, which caused the overall progress also to stall.

In the design and implementation phase, the management-emphasized approach favored proceeding from the module development towards the main system, while the author tried

to see main system structure and then manage the development process from above. This sometimes led to communication problems, which stemmed from the different perspectives of the parties. The selection of the programming language is essential in creating easily manageable code.

The author's opinion is that the automation project work was begun rather late and the management processes were inefficiently organized. The aim was first merely to create control software for a research vehicle. Later on, the project had to also consider public use, and the project planning was from then on processed semi-formally. This meant that most of the older software had to be rewritten in favor of better functionality, modularity, efficiency and reliability. Some of the changes in the equipment and software were opposed for a long time and were discussed on several occasions. The actual changes could have been made in less time than what it took to oppose said changes.

The author's opinion is that the management and organizational problems caused additional difficulties and delayed completion of this thesis. One of the greatest problems was the management's incapability to decide what the ultimate goal would be in terms of the intended use of the bus, as this sets very different design requirements for the system. Another major flaw was to forget the study of relevant regulations and the vehicle technology, and avoid the thorough planning of the control system in the beginning. These led to many technical and software related modifications in the later phases of the project. One good example was the air compressor, which was selected using the wrong specifications. Eventually it was discovered that the compressor output was not sufficient. This would cause the air dryer purge function to not operate at all, and the air suspension pressure to continuously stay close to the lower pressure limit. The replacement of the compressor required a new cradle assembly, new coolant hoses, a new wiring harness and new control software.

To be able to complete the design process in a truly comprehensive manner, it would need more time and resources than were allocated for this project Based on experience, the author would highly recommend that a project management strategy based on the V-model be implemented in future development projects at LUT. The methods proposed by the standards mentioned earlier in the work were found to be beneficial in the design process. In a commercial project, more work resources would be required to properly organize the operation in different processes, but following the guidelines is still recommended for any smaller group constructing a prototype vehicle, as they help to build a solid foundation for the design work.

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Risk assessment related examples.

Example of identifying dangerous situations related to accelerator pedal system.

Risk assessment (hazard identification)									
Machine		CAMBUS hybrid bus					**Method/tool**	risk graph	
Sources		Requirements, specifications, preliminary design					**Analyst**	JA	
							Current version	1.0	
Extent		Use: operation					**Date**	22.7.2015	
Method		Checklists ISO 12100:2010 annex B, system architecture/functions							
Ref. no.	**Type**	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario**				**Ref. no.**
					Hazard	**Equipment**	**Hazardous situation**	**Hazardous event**	
9	1	Use	Driving	Outside vehicle	Road accident	Accelerator	Accelerator signal; pedal system malfunction	Uncontrolled acceleration of the vehicle	9
9	2		Driving	Cabin	Passenger gets flung	Accelerator	Accelerator signal; pedal system malfunction	Uncontrolled acceleration of the vehicle	9
9	3		Driving	Cockpit	Driver gets flung	Accelerator	Accelerator signal; pedal system malfunction	Uncontrolled acceleration of the vehicle	9

Below, an example of the risk assessment related to the dangerous situations

Risk estimation

[x] Preliminary risk estimation

Product: CAMBUS
Issued by: JA
Date: 24.2.2015

Black area = High risk
Grey area = Medium risk
White are = Low risk

Consequences	Severity Se	Class Cl (Fr+Pr+Av) 0-4	5-7	8-10	11-13	14-15	Frequency Fr		Probability Pr		Avoidance Av	
Death, losing an eye or arm	4	SIL 2	SIL 2	SIL 2	SIL 3	SIL 3	≥ 1 h	5	very high	5		
Permanent, losing fingers	3		(OM)	SIL 1	SIL 2	SIL 3	< 1 h ... ≥ 24 h	4	likely	4		
Reversible, medical attention	2			(OM)	SIL 1	SIL 2	< 24 h ... ≥ 2 w	3	possible	3	impossible	5
Reversible, first aid	1				(OM)	SIL 1	< 2 w ... ≥ 1 y	2	rarely	2	possible	3
							< 1 y	1	negligible	1	likely	1

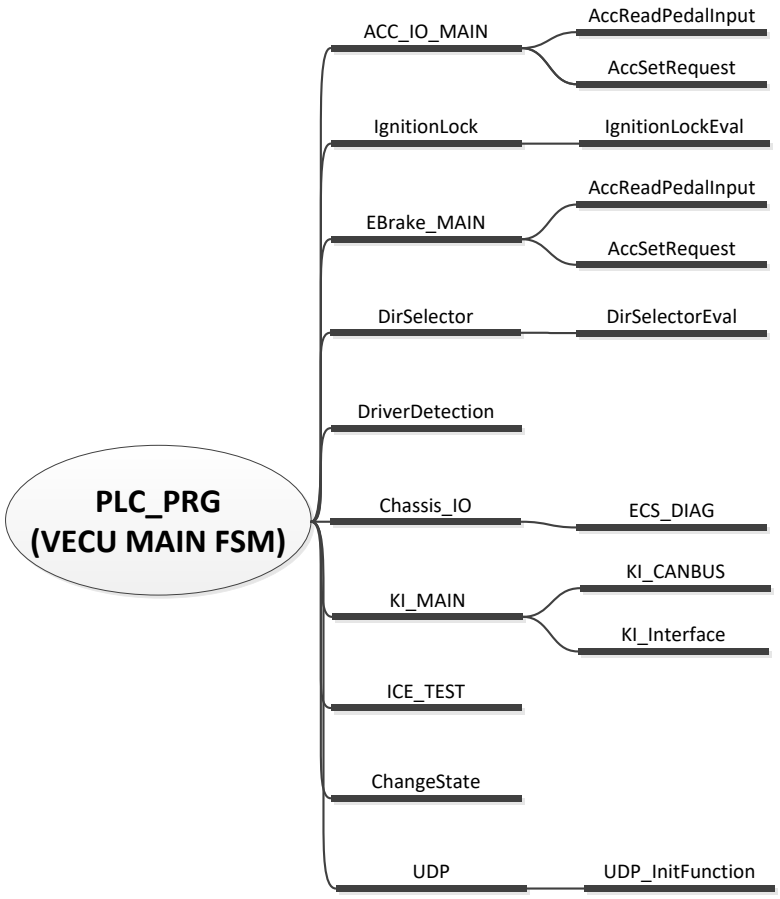
Ref nro.	Typ. Hzd. No.	Hazard	Se	Fr	Pr	Av	Cl	(SIL)	
9	1	Road accident, casualties	4	1	1	3	5	SIL 2	accelerator pedal subsystem failure
9	2	Passenger gets flung	4	1	1	1	3	SIL 2	accelerator pedal subsystem failure
9	3	Driver gets flung	2	1	1	1	3	0	accelerator pedal subsystem failure

An example of the risk estimation before and after the reduction by design.

Risk assessment (risk estimation and risk evaluation) and risk reduction														
Machine						CAMBUS hybrid bus	**Method/tool**					risk graph		
Sources						Requirements, specifications, preliminary design	**Analyst**					JA		
							Current version					1.0		
Extent						Use phase: operation	**Date**					24.2.2015		
Method						ISO 12100:2010 annex B								
Ref. no.	Risk estimation (initial risk)					Risk reduction	Risk estimation (after risk reduction)					Further risk reduction required	Ref. no.
	S	F	O	A	Cl	Protective/risk reduction measures	S	F	O	A	Cl		
9	4	1	1	3	5	Diagnostic functionality, which prevents uncontrollable acceleration in case of one failure . Brake pedal prevents acccelerator operation in all cases. Door brake. User's manual: use of hand brake at stops. Malfunction indicator light.	4	1	1	1	3	Suggest developing diagnostics further, use of safety PLC (1oo2D)	9

Program structure

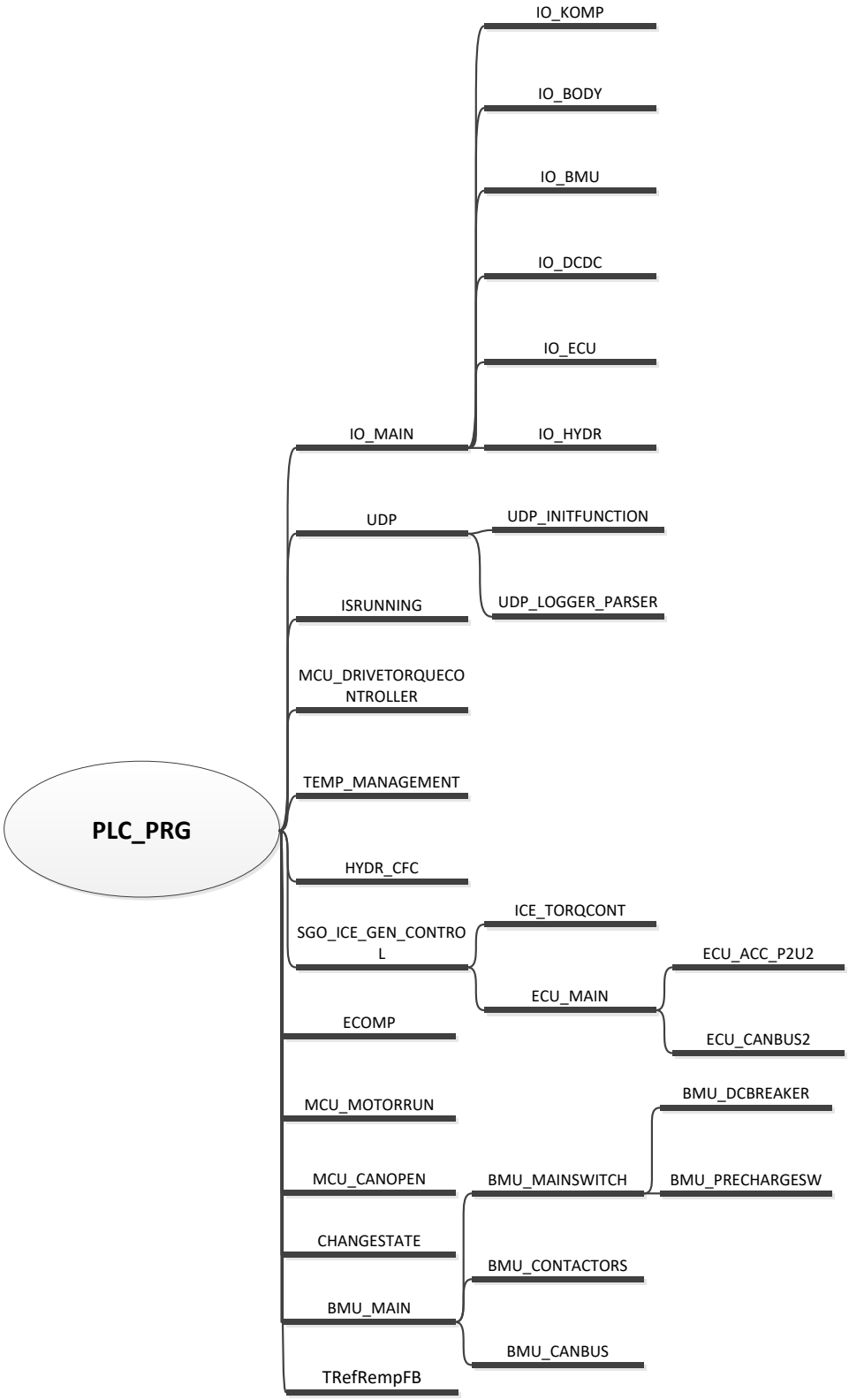
VECU program module tree



APPENDIX II, 2.

(continued)

HCU program module tree



Test case presentation

Documentation of a test case of VECU/AccReadPedalInput

Device/Program:	VECU
Component:	AccReadPedalInput
Type:	Function block
Description:	Component of accelerator pedal implementation
Language (IEC 61131-3):	ST
Version:	2016-03-10

Inputs

inputU	INT	(AI)
inputSK	BOOL	(DI)
inputKD	BOOL	(DI)
diag_run	BOOL	

Outputs

PedalPosition	WORD
IdleSw	BOOL
KickDown	BOOL
fault	BYTE

Used functions/function blocks/dependencies

ChangeState	FUN

Functional description:

Included in the header of source code

Design specifications, flow chart

Test date: 2016-03-10

Test type: blackbox, codesys

Test conducted by: JA

Test description:

- verifying function according to functional description
- verify operation with invalid inputs & BVS

Target description

PART 1

Verify processing of the analog and digital input signals

1. median filtering, implemented with OSCAT v3.3 library (61131-3, "no quarantees")
2. scaling (see limit constants) and conditioning of the output signal (0-1000)
3. input signal BVS, illegal values (e.g. WORD >> INT)
4. verify digital signal input filtering and output

PART 2

Verify the diagnostic functions for determining interface device faults. Cases

1. toggling operation of diagnostic features
2. signal too low (AI, self-reseting)
3. signal too high (AI, self-reseting)
4. signal static (AI, self-reseting)
5. signal change rate too high (AI, self-reseting)
6. idle switch implausible (AI, DI)

Test results

ID	Preconditions	Expected results	Actual results	Test result
P1-1	input *inputU* signal variable, random peak values. *diag_run*=false, others don't care.	peaks filtered, signal delayed by 5 cycles. *IdleSw*, *KickDown*, *fault*=false	peaks filtered, signal delayed by 5 cycles	pass
P1-2	input *inpuU* signal variable (low limit-high limit), *diag_run*=false, others don't care	output value *PedalPosition* must be within limits and behave according to design. IdleSw, KickDown, fault=false	*PedalPosition* value scales ok throughout the range	pass
P1-3	input *inputU* around configuration value boundaries, zero and over type range, *diag_run*=false, other don't care	*PedalPosition*: inside permitted range normal operation, outside permitted range limited to configuration values. out of type range must give 0. fault=false	BVS behavior as expected	pass
P1-4	*inputSK* & *inputKD*: toggle low-high with changing rate (well over configuration limit, rapid changes below configuration limit), *diag_run*=false, *inputU* don't care	*IdleSw* & *KickDown* must activate and deactivate according to the design; stable setting follows a high state, low input and short glitching produces a low state	behavior as expected	pass

APPENDIX III, 4.

(continued)

ID	Preconditions	Expected results	Actual results	Test result
P2-1	*diag_run*; toggle diagnostic operation on/off, monitor operational state	diagnostic functionality must activate/deactivate according to input *diag_run.* After P2-2, 3 or 4 toggle off/on must not reset *fault* state.	diagnostic functionality activates/deactivates according to input *diag_run. fault* ok	pass
P2-2	*diag_run*=true; permitted *inputU* -> below low limit configuration. hold permitted value. repeat x5	*fault*: “signal too low”. *PedalPosition*=0, *IdleSw*=true, *KickDown*=false. *fault* must reset / resume normal operation after a while without error.	*fault* reports correct error, pedal values ok, resets as planned	pass
P2-3	*diag_run*=true; permitted *inputU* -> over high limit configuration. hold permitted value. repeat x5	fault: “signal too high”. PedalPosition=0, IdleSw=true, KickDown=false. fault must reset / resume normal operation after a while without error.	*fault* reports correct error, pedal values ok, resets as planned	pass
P2-4	*diag_run*=true; *inputU* static in permitted range with inputs according to configuration	*fault*: “signal static”. *PedalPosition*=0, *IdleSw*=true, *KickDown*=false. *fault* must reset / resume normal operation after a while without error.	*fault* reports correct error, pedal values ok, resets as planned	pass

ID	Preconditions	Expected results	Actual results	Test result
P2-5	*diag_run*=true; inputU behaves normally with added PRBS (see configuration limits), *inputSK* as per normal *inputU* behavior	*fault*: “change rate too high/implausible”, *PedalPosition*=0, *IdleSw*=true, *KickDown*=false. must reset / resume normal operation after a while without error.	*fault* reports correct error, resets as planned	pass
P2-6	*diag_run*=true, *inputSK* behavior does not match *inputU* (see design & configuration constants)	*fault*: “idle switch implausible”, *PedalPosition*=0, *IdleSw*=true, *KickDown*=false. *fault* must not reset / resume normal operation after a while without error.	*fault* reports correct error, fault permanent	pass

Notes for further development

Calibration of the diagnostic parameters and limits suggested. No memory kept for discovered intermittent faults.