Metropolia

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Electrical design and implementation of a test bench for automated driving

Metropolia University of Applied Sciences
Bachelor of Engineering
Automotive Engineering
Bachelor’s Thesis
27 March 2023

Abstract

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Title:	Electrical design and implementing a test bench for automated driving
Number of Pages:	50 pages + 0 appendices
Date:	27 March 2023
Degree:	Bachelor of Engineering
Degree Programme:	Automotive Engineering
Professional Major:	Automotive Electronics Engineering
Supervisors:	Ert Ülle, electronics engineer Mikko-Matti Kauhanen, people lead

As the trend of autonomous driving is the new normal of the near future, many companies have risen to accept the challenge for improving and perfecting these technological milestones. A Finnish based but also internationally recognized and award winning Sensible 4 is one these companies. What makes Sensible 4 to stand out from its competitors is the ability to tackle the all-weather challenge making the vehicles capable for autonomous driving in any weather condition.

Sensible 4’s main product is the autonomous driving software. As is the case with all the software, a huge amount of testing is required to make sure everything is working in a way that has been planned with zero exceptions. This is even more true when it comes to the software that has even the slightest possibility of making mistakes that in the worst-case scenario may cost human lives. Testing the product is an essential part of the software development.

The main topic of this paper is a Sensible 4 project concerning the electric design and implementation of the test bench that is made for the software and hardware bench marking, testing and development. With this product, the company is filling one gap of the testing scenarios which also widens the automated testing possibilities for endurance testing and stress testing of the software and the equipment.

Test bench is a cubic metal framed physical platform with its own wheels for moving. It is only being moved around by pushing it. The platform enables all the autonomous driving sensors and computing units to be installed on it and it has also its own power supply with approximately 2 hours working time when using the battery power.

The autonomous driving kit, including the computing unit and the sensors, was already established for the test bench while the wiring harnesses for power feed, ground potentials, sensor signals and protective devices were a subject to be designed and implemented. The result of the project was a working device with all the set objectives reached.

Keywords: autonomous driving, test bench, wiring, schematic

Tiivistelmä

Tekijä:	Mikko Arlin
Otsikko:	Electrical design and implementation of a test bench for automated driving
Sivumäärä:	50 sivua + 0 liitettä
Aika:	27.3.2023
Tutkinto:	Insinööri (AMK)
Tutkinto-ohjelma:	Ajoneuvotekniikka
Ammatillinen pääaine:	Autosähkötekniikka
Ohjaajat:	Sähköinsinööri Ert Ülle Henkilöstöpäällikkö Mikko-Matti Kauhanen

1900-luvun lopun tietokoneaika ja teknologiamurros ovat muovanneet koko aikakautta voimakkaasti ollen avaintekijä modernin yhteiskunnan muodostumisessa. Ajoneuvotekniikka suhteellisen nuorena teollisuuden alana ja insinööritieteenä on ollut osana tätä nopeaa muutosta, ja yhtenä uusimmista alan innovaatioista voidaan pitää autonomisista ajamista.

Sensible 4 on kansainvälistä näkyvyyttä ja tunnustuksia kerännyt suomalainen yritys, joka toimii autonomisen ajamisen kentällä. Yrityksen tulokulma autonomiseen ajamiseen on keliriippumattomuus, jolla tarkoitetaan kykyä autonomiseen toimintaan kaikissa keliolosuhteissa.

Sensible 4:n päätuote on autonomisen ajamisen ohjelmistokoodi ja kuten kaikessa koodissa, testaaminen on ensiarvoisen tärkeää. Testaamista tarvitaan ennen kaikkea toimivuuden ja laadunvarmistukseen, ja ohjelmistokoodin virhemarginaalin on pysyttävä hyvin pienenä. Testaamista helpottamaan ja monipuolistamaan sekä samalla uusien komponenttien valintaprosessia tukemaan nousi tarve saada oma testialusta.

Tämän insinöörityön pääaihe on testipenkin sähkösuunnittelu ja toteutus. Testipenkki on omilla renkailla oleva metallirunkoinen alusta, joka mahdollistaa komponenttien kiinnityksen ja niiden käyttämisen testaustarkoitukseen. Testipenkkiin on asennettu Sensible 4 -yrityksen valmistamissa autonomisissa ajoneuvoissa käytetyt anturit sekä tietokone, ja se on lisäksi varustettu omalla virtalähteellä, joka mahdollistaa noin kahden tunnin mittaisen käytön ilman verkkovirtaa.

Autonomiseen ajamiseen tarvittavat anturit, tietokone ja muut komponentit ovat samat kuin autoissa, mutta sähkösuunnittelu ja toteutus eroaa autojen tilanteesta ja vaati näin ollen erilaisia ratkaisuja. Työlle asetetut tavoitteet saavutettiin ja puuttuva testausalusta tulevaisuuden ohjelmistopäivityksiä, muita kehitysversioita ja komponenttivalintoja silmällä pitäen valmistui käyttöön.

Avainsanat: autonominen ajaminen, testipenkki, johtosarja, kytkentäkaavio

Contents

List of Abbreviations

ABS: Anti-Lock Braking System. A system preventing wheel from locking up during braking.

AD: Autonomous driving. Driving without a human controlling the vehicle.

AD-kit: Autonomous driving kit. The autonomous driving system consisting of computing unit and the sensors.

ADAS: Advances Driver Assistance Systems. A group of different human-machine technologies to make driving safer, easier, and more convenient.

ADCU box: A cubic metal box located inside the vehicle. The box includes AD computing unit, several control units and power feed plus fuses for the AD-kit.

AVP: Autonomous Vehicle Platform. Software of the Vehicle Control Unit which controls the Drive by Wire functionalities.

CAN: Control area network. A robust communication network for serial communication between control units.

CRC: Cyclic Redundancy Check. A defined logical algorithm for counting if the CAN information has been correctly passed.

CSA: Cross-sectional area. In this paper CSA is describing the thickness of conductor’s cross-sectional copper area for current carrying.

DbW: Drive-by-Wire. Electrical system for controlling the vehicle’s movement.

DC: Direct current. Electronic current that travels always to same direction.

EV: Electric vehicle. A vehicle that uses electric motors for propulsion.

GNSS: Global Navigation Satellite System. A system that uses satellites for positioning globally.

HIL: Hardware in the loop. Combined hardware and software testing procedure often done with the help of a test bench.

IMU: Inertial measuring unit. An electronic device that uses different sensors for reporting the angular rate and the specific force of the unit itself.

LTE: Long term evolution. Wireless broad band data transmission standard.

OEM: Original equipment manufacturer. Company that is producing or selling the non-aftermarket goods as their own.

PoE: Power over Ethernet. A system that passes electric power along with data on the twisted pair ethernet cabling.

RTK: Real time kinematics. An application for correcting errors in the satellite navigation system.

TEHI: Touch encoder human machine interface. A controller that combines a touch screen, a rotary switch, and a keypad.

UPS: Uninterruptible power supply. Power bank for powering electrical devices without wall socket.

USB: Universal serial bus. An industry standard that includes protocol, connectors, communication, and power supply for connecting computers and peripherals.

VCU: Vehicle Control Unit. Computing unit run by the AVP-software which controls the Drive-by-Wire components.

1 Introduction

Automation and unmanned tasks executed and supervised by a computer have benchmarked their need as being the new normal of the western civilization for several decades now. The achievements of the late 20th century modern technology have made robotics and artificial intelligence strongly involving the design and implementation for being “the way of the future”. From this perspective, the same ideology is also becoming heavily involved in the vehicle industry and transportation. The next goal is leaning towards the automated driving, which is why the vehicle technology is using remarkable amount of money and time to meet these needs. (Kaas & Others 2016: 11.)

There have been many successful stories of self-driven, or almost self-driven cars already in the past, one of the most famous ones being Tesla’s autopilot. Advanced driver-assistance system features like adaptive cruise control, lane keeping, and emergency braking are standard accessory for at least premium segment cars and are nowadays also found in more affordable daily driven cars. (Rudhart 2019: 9.) These stories mentioned above are usually lacking the fact that autopilots and ADAS-features drop out when the weather conditions are no longer suitable for clear and undisturbed visibility. These harsh weather conditions can include rain, snow, fog and/or icy surfaces, to name a few, which are not uncommon in Finland and many northern countries around the world.

Sensible 4 is Finnish company founded 2017. The company is developing and producing autonomous vehicle software and, in many cases, also the hardware implementation is executed by the company. Developing the software, but also making the hardware design inhouse, enables the perfect compatibility, which leads to the experience of flawless automated driving for the customers. It also enables the demonstration of behaviour in the pilot projects. What makes Sensible 4 to stand out from its competitors is the all-weather capability, which has been the target of the development from the first day on. Several other pilot projects are ongoing at the moment, showcasing these same capabilities in different countries. Some of these pilots' use cases are focusing on the industrial use of the autonomous driving and some on the last-mile transportation for people.

2 Project overview and purpose

It is worth spending an extra couple of minutes to understand the overall picture of the company's product. After that, it is more convenient and clearer to get into the details of this thesis.

2.1 System description of the Sensible 4 main product

As mentioned in the previous chapter, Sensible 4 mainly concentrates on automated driving software development. Nevertheless, it is obvious that no self-driven vehicle can perform the needed functions only with the aid of the software. The AD hardware, including several sensors, is also needed for providing the data that AD software is dealing with. The company's product focuses strongly on the software side but several customer projects also include the hardware implementation. Software can be tested as a standalone product with different software testing tools but when the hardware is also involved it is essential to do the testing with the whole AD kit using hardware in the loop method. HIL is natural next step often executed with a test bench after the software in the loop procedures have been finished. HIL testing is done before the actual road testing with real vehicles begin. (What is Hardware-in-the-loop testing? 2022.)

The software runs in the AD control unit, which is a powerful computing unit located in the vehicle. Software receives a stream of data from the sensors consisting of lidars, radars, cameras and sensors dealing with localizations, movement and odometry. These sensors are providing the needed data for the obstacle detection and trajectory following which is carried out by localizing the vehicle on the map. A precise localization is extremely important for the all-weather driving since clear output from for example the lanes of the road cannot be received. Sensible 4 performs the accurate localization with the previously mentioned sensor data, global navigation satellite system (GNSS) and the odometry of the vehicle itself. With the data received from the sensors, the position can be calculated precisely enough to perform safe autonomous driving in any weather condition. (System Description of the Autonomous System 2021.)

After receiving the data from the sensors, the AD software processes it. Based on the received data, the AD software is passing commands for the actuators to perform the actions needed to move the vehicle with the desired speed, acceleration and direction. The actuators together with their controlling units, are the so-called drive-by-wire (DbW) system. The vehicle control unit often referred as the VCU, is responsible for receiving the commands via CAN-bus from the AD software and sending the commands to the control units of the actuators respectively. In some cases, the VCU is controlling the actuator directly. VCU is running Autonomous Vehicle Platform (AVP) software which holds all the commands for moving the vehicle. All the vehicle specific parametrizations are set in the code. The VCU is also responsible for the logging and interpreting the OEM CAN-bus traffic to get the necessary status of the car. Some CAN messages can also be sent to the vehicles OEM CAN-busses, and this function is executed by the VCU, as well.

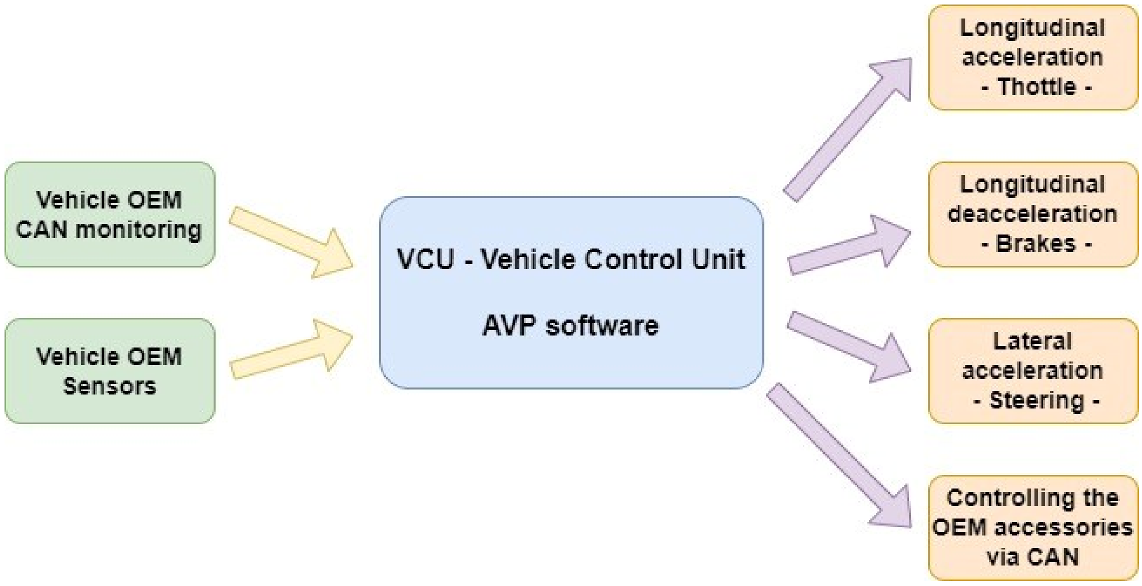

Figure 1. Inputs and outputs of the VCU.

In the picture above, all the outputs described as functions of the VCU are illustrated, as well as the input parameters from the OEM sensors, and the OEM CAN bus of the vehicle.

2.2 Purpose and requirements

The need for this project was obvious. It is essential to have an easy and adjustable HIL platform for mainly testing purposes. The platform should have an easy access to configurations, and it should be used without any vehicle. All the use cases are at the same time the main purposes of the test bench's existence:

- Testing and configuring sensors before the installing them to the vehicles.
- Scouting and benchmarking of the sensors and other hardware for the long run.
- Continuous testing, especially after new software releases with the actual hardware.
- Longer endurance testing for the hardware, software and data logging.
- Fault case simulations with failing hardware.

Brainstorming the test bench had begun already before I joined the company. The need was already existing, but the actual launch for this project happened during the summer 2022. First meetings with the managers, AD-software engineers and the vehicle development team were crucial to defining the specifics for the test bench. The purposes for the test bench mentioned above had to be made to match with the requirements of the hardware, which were:

- At the starting point the sensor set for the testing should be the same that has been utilized with the retrofitted autonomous vehicles lately.
- Calibrated sensors are needed to perform proper software tests.
- Modular design for the future modification and additions.
- Mobile design for moving the bench easily:
  - Wheels for moving the test bench since it will be heavy with all the components and accessories attached.
  - Lifting possibilities (forklift) for lifting the bench to the van if testing is needed to be done somewhere else.
  - UPS 230 V power source for powering all the electrics and electronics for minimum two hours.
  - Onboard Wi-Fi for the Internet connection needed for the AD-software.
  - Screen, keyboard, and mouse included for easy access to the computing unit, which eliminates the need of bringing anything to the test spot.
- Modularity for computers: possibility to use different computing units (ADCU box, standalone Vecow PC and Nvidia platforms).
- Full sensor kit (lidars, radars, cameras, other sensors).
- VCU should be included for the testing of the AVP-software.

When the scope for the test bench was decided, it was also decided what will be left out of the scope of the project. The modular design will enable nearly anything to be added at the later stages. The main things left out were:

- Possibility to unlimited system testing (e.g., testing of any wiring harness for any vehicle would be too universal and make the design too complicated).
- Actuator testing of the DbW-system.
- Waterproof testing outside or in the wet conditions for e.g., new hardware bench marking.

- Electromagnetic compatibility testing (EMC conditions of the test bench frame differs somewhat from the vehicle's body being "closed metal box").

The mechanical parts were designed and assembled during the late summer and autumn of 2022 by co-employee, mechanical designer Teemu Saarelainen. His experience of 3D-designing was priceless, and he did fantastic job also with the assembly. The bench with all the details looks excellent, and besides, it is also practical.

When comparing the test bench and an autonomous vehicle equipped with Sensible 4 AD-kit, it can be stated that the test bench has nearly all the sensors that the high-level autonomous driving software needs. What is missing from the sensor data side is the odometry of the vehicle. The motion sensors, which in the vehicle use are the OEM wheel speed sensors, are being logged from the OEM CAN-bus of the car itself. Since the test bench doesn't have toothed rings or magnetic ABS-rings on its wheels, it is challenging to calculate the odometry from the wheels. The test bench also lacks a steering wheel and a steering wheel angle sensor, so no input for the desired or travelled direction can be acquired.

DbW-system and, to be more accurate, the DbW-system control units, actuators, and sensors which are brake actuator, brake pedal detection, electronic power steering motor, electronic parking brake, emergency deactivation push button and a throttle control system with respective control units are also missing from the test bench. Although the actuators do not exist in the test bench, it does have VCU which is industrial grade control unit manufactured by Bosch. VCU is on the test bench to test AVP-software that is controlling the DbW-system and also for the CAN communication between the AD-computing unit and the VCU.

These forementioned features were decided to be dropped out due to physical dimensions and since there is no actual need for them in the testing. Including these features would also make the electrical and mechanical design much more complex. In addition to those, some of the accessories that Sensible 4's autonomously driving vehicles have e.g., turn indicator lights and electric sliding door controls, has been as well excluded from the test bench for the reason that there is no doors or lights in the test bench. As stated, and thanks to the modular design, almost anything can be added to the test bench later, if needed. (Meeting notes.)

2.3 Electrical system overview

The subject of the present thesis consists only of the electrical design and implementation of the test bench, which is why the mechanical hardware and all the software considerations have been left out. Also, the electronic devices, such as sensors, were a subject that were already considered and purchased, so the thesis does not include the benchmarking of these equipment. As stated above, the electrical design of the autonomous systems is made to somewhat match the electrical system of the company's recent products. The sensor set and other devices are mostly the same that has been used on the latest Toyota Proace EV passenger van, which is the main last mile solution for the transportation of people at the moment. The most significant difference between any autonomous driving vehicle and the test bench is the power feed of the electric instruments. Cars equipped with internal combustion engine are electrically powered by the alternator and the same source is powering the AD-kit as well. In case of electric vehicles, the traction battery with a step-down converter for the voltage is ultimately the power source of the AD-kit. The test bench has its own energy source that differs from the vehicles significantly.

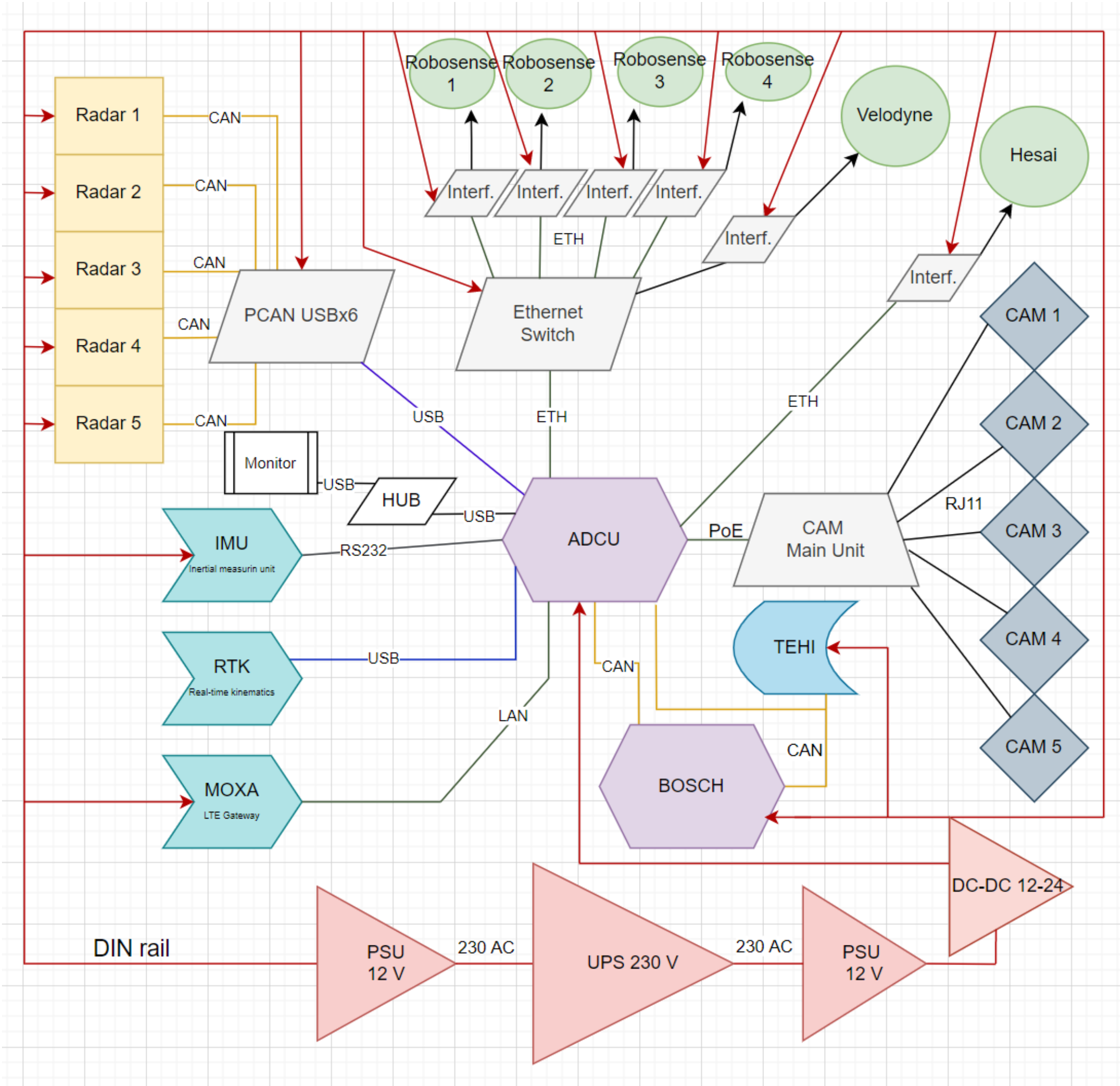

Figure 2. Test bench's simplified electrical system illustration.

On the picture above is the simplified conceptual model of the test bench's fixed electrical equipment. It includes all the AD-kit devices and does not include the DbW-system as mentioned. The model also lacks complete wirings, connectors, and fuses as well as some minor details, like the navigation antenna, has been left out.

2.3.1 Power distribution and signals

As it can be seen in the figure 2 above there are three different power supplies and one DC-DC-converter. Uninterruptible power supply (UPS) is the energy source for the whole system. It can be used as a stand-alone lithium-ion battery powerbank with 2016 Wh capacity, or direct power source when being connected to the power outlet via wall socket. UPS provides normal 230 AC voltage for the laboratory power supplies. Test user’s laptop can be charged from these ports as well. It also has a couple of different USB outputs with different amounts of current (fast charge provided as well). The li-ion battery powered station with NCM cell chemistry has its own battery management system, and it is protecting the device for example from voltage surge, overload, and short circuit. (EcoFlow DELTA Max Portable Power Station.)

The test bench has two adjustable switching mode DC power supply units (PSU). Both PSUs are powered via standard 230 VAC schuko cable by the UPS. One of PSUs can provide a range of voltage between 0…15 Volts and the other one can be set to as high as 32 Volts. For the test bench, both are set to 12 Volts, but it is useful to have the ability for higher voltages in case of testing for example new sensors with higher operating voltage. PSUs are both providing the maximum of 60 Amperes, and they also have nice feature for a short circuit protection and several other protective devices such as overload protection and over-temperature protection. They are load sensitive and will limit or cut off the constant current if anything exceptional is detected. (HCS-3600/3602/3604 USB User Manual 2022; SPS-9600/9602 User Manual 2021.)

A DC-DC-converter is located close to the power supplies. The purpose of the converter is to rise the voltage level to meet the demand of the Vecow PC, which is the AD computing unit. There was also the option for executing this directly using the power supply unit that can provide the needed 24 Volts but it was decided to do this conversion by using the same DC-DC-converter as is in the case of the Proaces. By doing this, the manner for providing the sufficient voltage levels to all the components is matching the autonomous vehicles. The flip side of the coin would be the increased number of components (extra DC-DC-converter and the wirings needed), weight and costs. In the case of using the ready-made ADCU-box from a car the DC-DC-converter is located inside the box and the external DC-DC-converter will not be needed. This was considered when designing the interchangeability between these two use-cases.

Figure 3. UPS, PSUs and DC-DC-converter.

The power distribution for the devices is divided between the two power supply units in the manner that the maximum output amperes (60 A each PSU) will not be surpassed at any loading circumstances. In some datasheets, the needed normal operating currents were informed when the other datasheet only provided the maximum power that the device is consuming. For calculating power, a formula (1) stated below is used and from the same formula the current can be also calculated when the power consumption is known.

$$P = U * I \qquad (1)$$

The division between the two PSUs is that one of the PSUs is only powering up the PC and the other one is being used for all the other devices. The Vecow PC can also be equipped with its own power supply that outputs 600 W, which by using the formula refers to 25 A current in 24 Volts. A stress tests for the DC-DC-converter previously run for the Sensible 4 purposes gives measured ratings of over 30 Amperes under a maximum load of the PC. (Static Vehicle Test 7 Report, ADCU Stress Test 2020; 02.8-SVT-PEV2 Power Draw Load Stress Test Report 2021.) Taking that into account and also the fact that the bench will be used in future with a Nvidia computing unit, which has not been stress tested yet, it was justified to leave some head room for the future and provide the 60 A for the PC and rest from the other power supply.

2.3.2 Lidars

The lidars are located around the bench and all of them have their own interface. Each interface is powered, fused and the interface handling the power supply and communication of the sensor. The operating voltage of all the lidars is 12 V but as in most electronic components there is some tolerance for the voltages (RS-Bpearl User Manual. 2020). This comes handy and needed in the vehicle adaptations, especially when the vehicle is powered by internal combustion engine. A charging voltage provided by an alternator can fluctuate and if the car is equipped with a start-stop-functionality the battery voltage level can drop below 12 Volts for some time when the engine is not running. The datasheets of the products provided either the needed maximum amperes or the power that each component is using. Some of the datasheets only provided average or typical numbers of drawn amperes or consumed watts, thus, these numbers were used when calculating while the maximum amount stayed unclear.

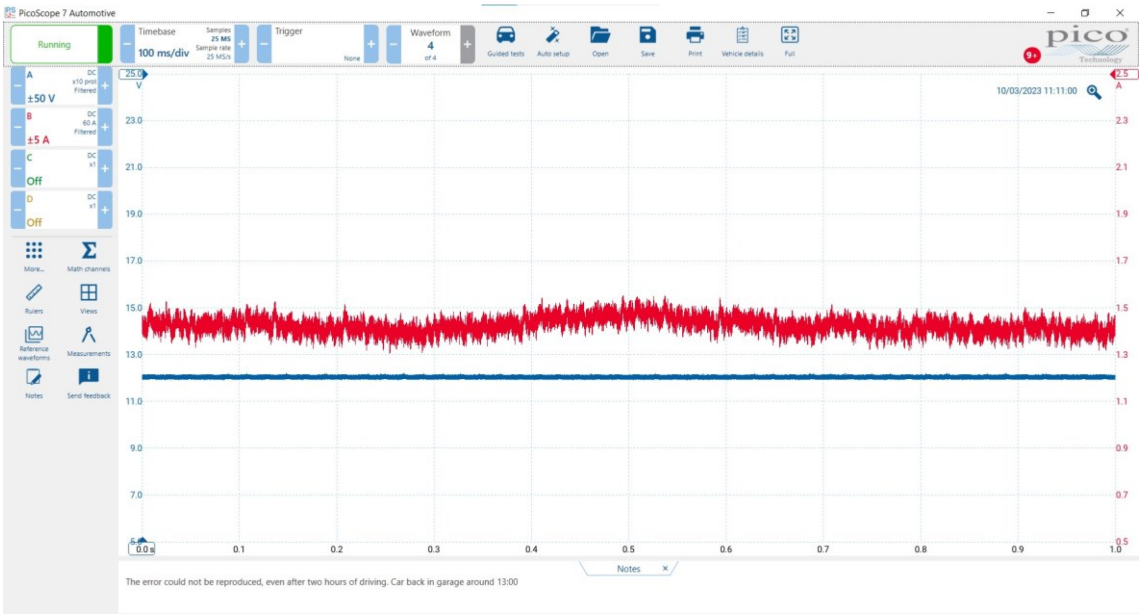

Figure 4. Current consumption and the operationg voltages of a Robosense lidar unit measured with an oscilloscope.

In the picture above (figure 4) the current consumpition can be seen in Amperes (red) while the operating voltage (blue) is staying close to 12 Volts all the time. The Robosense RS-Bpearl User Manual states the normal operating power being 13 Watts which yields to approximately 1,08 A current draw. In the oscilloscope measurement, the current draw was a bit higher being around 1,4 A and the operation condition was rather normal. With this observation, it is justified to always leave a slight head room for the implementation and not only stubbornly stick with the made calculations.

There are altogether six lidars from three different manufacturers included in the test bench, as is the case with Toyotas as well. Five out of six lidars are using an ethernet switch, which is acting as a communication interface between the PC and the interfaces of these five lidars. Only one lidar, manufactured by Hesai, is connected to PC via interface of its own and is not using the ethernet switch for communication. As Hesai being the main lidar, it is faster and more robust with increased redundancy when connected directly to the computing unit. All the lidar interfaces and the ethernet switch are using ethernet cables for the data transfer, while the power and ground is provided in a separate connector. Ethernet switch is also 12 V device and has a minimal power consumption of 5,8 W so the needed amperes are only less than 0,5 A (EKI-2728/I Ethernet Switch Datasheet 2018).

2.3.3 Radars and cameras

Test bench has five radar units manufactured by Continental. According to the datasheet, the radars are operating in 12 Volts and each of them is consuming 12 W of power (ARS 408-21 Long Range Radar Sensor 77 GHz Datasheet.) By using the equation 1 above it is easy to see that each unit needs 1 A current to work, so with five radars it means 5 A current total. The communication of each radar happens via CAN-bus, respectively, and therefore an interface is needed between the sensor and the computing unit. Each radar is connected to Peak System PCAN USB X6 CAN interface that is acting as a CAN gateway unit. It is responsible for transceiving and receiving the CAN messages, modifying them to match the USB protocol and sending them to the AD-computing unit in a format that the AD-computer can understand. CAN interface is also CAN FD compatible but in the test bench only regular CAN communication is being used. For future use and the hardware selection/testing procedure, the CAN FD possibility might turn out to be a handy feature. The interface is consuming little power and it is only demanding 0,35 A of current at 12 V, according to the datasheet. (PCAN USB X6 User Manual 2022: 34). To avoid interference from the signal echoing, the CAN-bus is typically terminated with 120 Ohm resistor on two farthest nodes of the network (TI Designs: TIDA-01238 2016: 1.) The CAN-bus of the radars is terminated from the end points of each radar unit. On the CAN interface end an optional termination was carried out by soldering a passage inside the circuit board of the device leading the signal to the resistors in the end point. (PCAN USB X6 User Manual 2022: 12-15).

The test bench has the same cameras that Sensible 4’s retrofitted vehicles have, and there are five of them in total. Four of the cameras are facing front, rear and both sides of the test bench frame and one of them is facing to the “driver” of the test bench. The cameras are controlled and powered by a main unit that is powered by the PC via power over ethernet (PoE). This means that no separate power supply for the cameras or the cameras' main unit is needed since everything has been taken care of with the PoE that has been standardized by IEEE. Although PoE is used for carrying power in the unfused wire, it is safe to use. The power consuming devices that are powered via PoE are usually consuming a small amount of power and the PoE method is utilizing semiconductor materials that are programmable. In the case of any fault, it can be turned to non-conducting state in every 400 milliseconds. (Card 2021.)

2.3.4 Other sensors and devices

Other sensors and devices that the test bench has are inertial measument unit (IMU) for the measuring of the different acceleration and angular speed, real-time kinematics unit (RTK) for GPS/GNSS satellite navigation, LTE gateway for the Internet connection and touch encoder human machine interface (TEHI) for user interface for choosing between the autonomous mode and manual mode. As mentioned previously, the test bench has a fixed monitor that is powered by the PC via an interface. USB-C connection will provide the necessary energy for the monitor and the interface. Test bench's IMU is a tiny sensor using micro-electro-mechanical-system technology and gyroscope that sensitively measures inertial changes, which is used for example navigation of the unmanned vehicles, artificial horizon, and robotics (MicroStrain Sensing Product Datasheet). The power consumption of the device is 500 mW meaning 0,042 A current in 12 Volt system. IMU is connected to the PC using the OEM-cable with in-house made extension to it. The connector on the device end of the cable is a micro-DB9 on the PC end a regular DB9.

RTK stands for real time kinematic positioning, and it is an application for determining position with error correction. The method is basically the same as differential GPS error correction is doing and it is much more accurate than the uncorrected GPS signal. With the use of RTK the accuracy of the position can be determined in centimetre-level. (Wanniger 2008.) On the test bench the RTK standalone board is a USB powered item manufactured by Ardusimple with an in-house printed plastic case around it (figure 5).

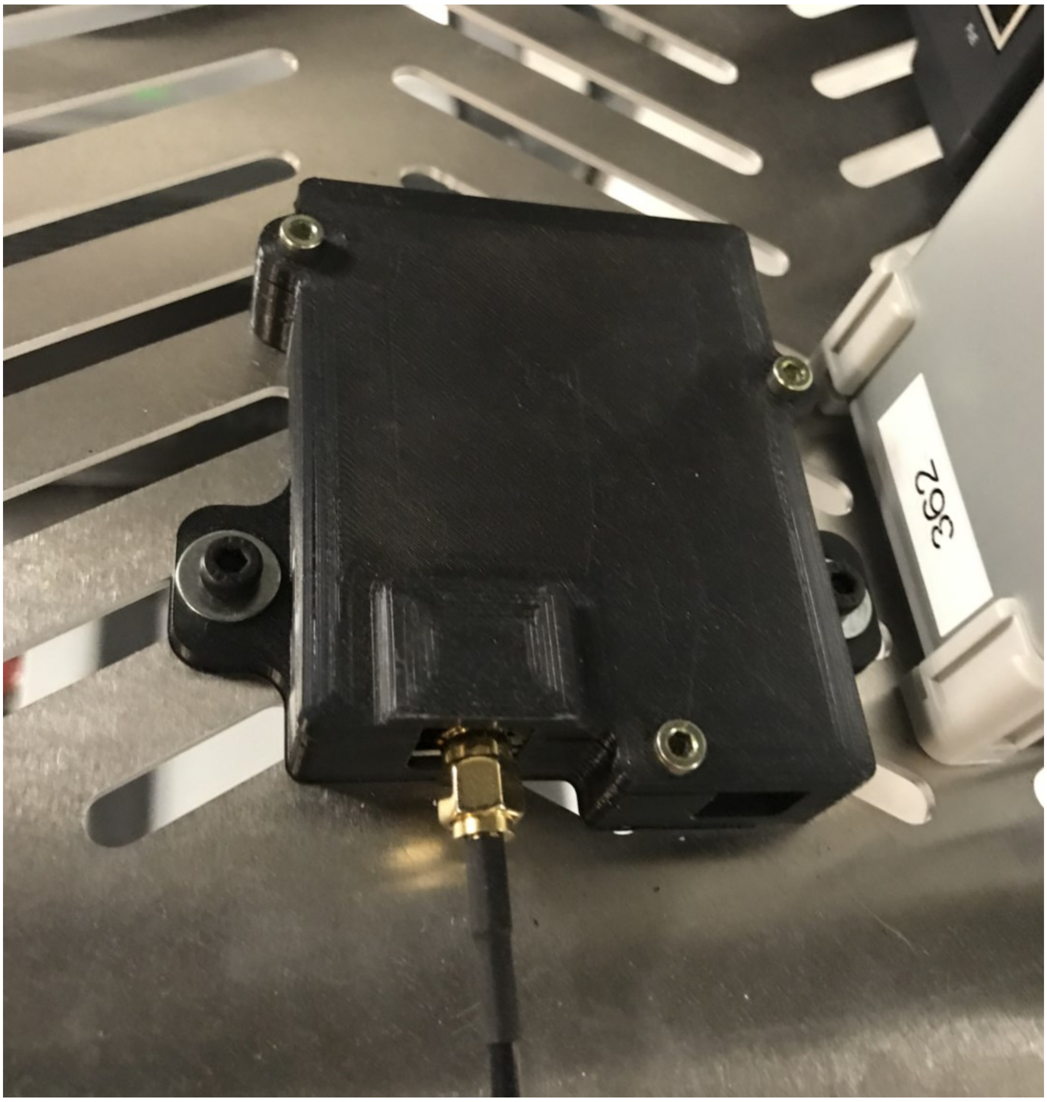

Figure 5. RTK-unit with the 3D-printed plastic cover.

Since it is using USB for power and communication, there is no need for wiring or fusing the connection with self-made wiring harness. RTK board is connected to the GNSS antenna located on the top of the test bench frame. The antenna is multiband type for better accuracy and powered by the RTK receiver board demanding 3,0…5,5 Volts for operating. Wiring is regular coaxial RF cable with TNC/SMA connectors, and no fusing is needed for this. (SimpleRTK2B Budget.)

MOXA is the manufacturer of the industrial level 4G LTE cellular gateway with option for two sim-cards for increased redundancy. According to the datasheet of the gateway, the operating voltage can be anything between 12…48 Volts and at 12 VDC the current needed is 0,7 A (Moxa OnCell G3150A-LTE Series Datasheet: 3). For electromagnetic compatibility, the power connector is also having a pin out for the frame ground cable. Moxa OnCell also has a reverse polarity protection for protecting the device in a serious voltage issue of miswiring the positive and the ground conductors. Moxa is connected to the PC and for that purpose an ethernet cable is being used. In the vehicle use the device is connected to two LTE antennas that are located on the roof of the car but on the test bench the open structure of the frame provides sufficient clearance for the antennas to be connected directly on the body of the gateway. (Moxa OnCell G3150A-LTE Series Datasheet.)

Touch encoder human machine interface, which is often referred to as TEHI, is acting as a graphic user interface for the AD. It is part of the DbW-system switching the functions between the autonomous mode and the manual mode. It is a small touch screen with a rotary switch for scrolling. Since the test bench does not have automated driving, the switching is not needed for that but for testing purposes there is a need to launch the automated mode for monitoring the AVP software behaviour. The datasheet is providing info for the component’s operating voltage to be anything between 4,75…18 VDC and at its maximum screen brightness the power consumption is 1,5 W. Hence rather small current is needed being 125 mA. (Touch Encoder Datasheet.) TEHI is communicating with the PC via CAN-bus. On the TEHI end of the CAN-bus a split termination is being used. It is basically a low pass filter for filtering out the unwanted noise and interference from the signal which improves the electromagnetic compatibility of the circuit (Corrigan 2008: 7-8).

2.4 Wire dimensioning

For the electrical systems, it is essential to have the proper conductors to carry out the needed task which is distributing power and signals (Bosch Automotive

Electrics and Automotive Electronics 2007: 394). In other words, suitable cables and wiring harnesses form the essential backbone of the whole electrical system. In the previous chapter, the power consumptions and the current draw were explained with the case of every component. In this chapter, by using the previous information, it is calculated how the current draw is affecting the wire dimensioning.

When selecting a suitable cable for any electrical device, one needs to consider the length of the cable, the cross-sectional area of the cable, current that the cable is carrying, the material dependent resistance of the cable, to mention a few. A greater amount of current in conductor causes greater resistance due to the resistivity of the conducting material. Resistance is acting as a function of temperature meaning that the temperature of the conducting material rises when the current is flowing. As the temperature rises, the resistance also increases. In the dimensioning point of view, the rule of thumb is that the length of the conductor is proportional to the resistance of the conductor. On the other hand, the cross-sectional area of the conductor is inversely proportional to the resistance of the conductor. This means that the longer the cable is, the thicker it must be also taking into consideration the surrounding circumstances especially in a temperature point of view. (Juhala & Others 2005: 14.)

When determining the cross-sectional area, a resistance of the conductor is essential to know. The resistance is dependent on the length of the cable and the conducting material, as well as the CSA itself. Resistance is calculated by using the equation below.

$$R = \frac{\rho * l}{A} \qquad (2)$$

In the equation, the R is the resistance, ρ is the resistivity of the conducting material, l is the length of the conductor, and A is the CSA. In the field of electric designing of the cars the so-called chassis ground return is often being used where the body of the car is used for the ground point of every ground connection and the return path for the current flow back to the current source. In the case of the test bench, the chassis ground was not used. Instead, ground conductors were used for each sensor and device per se. This was done mainly because the frame of the bench consisted of several pieces, which were mechanically attached to each other. The material of the frame parts were different from each other, although all of them consisted of metal. Also, something worth noticing is that while the frame parts are different metals, they also have different coating which will affect the conducting ability of the ground side. It will have a significant impact for the whole electric system if the resistivity of the frame ground is greater than tolerated. That can be caused by poor or loosened connection between the chassis parts. Poor connection on any part of the electric circuit or the discontinuity of the current carrying potential caused by material will lead to risen resistance of the circuit that results to the greater voltage drop. For more accurate results, the whole length of each circuit needs to be considered, and in the case of the test bench, the length cannot be calculated by measuring power or ground conductor and multiply by two. The routing of the harnesses may differ a lot depending on the location of the component that is being powered up and all the power feeding positive conductors are routed via switch plate which is discussed more in the further chapters.

The resistivity of the conducting material is not only dependent on the material itself, but also the temperature of the material. In the case of the test bench the material of all the conductors is copper that has a resistivity of 0,0172 $\Omega mm^2/m$ in the temperature of 20 °C. Since the test bench in only used indoors in a steady room temperature and the warming of the cable due to resistance can be assumed to be quite meaningless. The current flow of any conductor of the bench is rather small since the power consumptions of the devices are small as well. That is why the temperature correction for the formula does not need to be considered in this use case. However, the equation to use for the temperature correction is stated below.

$$R = \rho \frac{l}{A} = \rho_0 [1 + \alpha(T - T_0)] * \frac{l}{A} \qquad (3)$$

In the equation, the ρ_0 is the resistivity of the conductor in 20 °C, α is the temperature coefficient for the material of the conductor, T is the maximum temperature that the cable experiences, T_0 is 20 °C.

Any resistance in the conductor leads to voltage drop, and as the resistance cannot be avoided in the temperatures above the absolute zero it has to be considered in the calculations. As Kirchoff's circuit law of voltage states, voltage drop leads to less operating voltage on the device. In the worst case of major voltage drop on the wrong part of the circuit would lead to the electrical device not working in the way it is designed to. For automotive industry a standard for maximum tolerated voltage drop for any circuit doesn't exist. Although a standard for voltage drop in a starter for circuit does exist and it states 0,2 V drop for non-commercial vehicles meaning approximately 1,7 % in a 12 Volt system. However, for the vehicles equipped with an internal combustion engine, the starting circuit is the most crucial part voltage drops. A major voltage drop due to unwanted resistance in the circuit can cause poor cranking and no start condition especially during cold season. In an outdated aviation standard (SAE AS50881 1998) an outdated military standard (MIL-STD-704F 2004) was being referenced for the voltage drops. These versions are still valid for the voltage drop sections since the Ohm's law hasn't changed during the last decades. The military standard states 0…2 V voltage drop for 24 Volt systems to be within the tolerance. This means approximately 8,3 % voltage drop. Hence depending on the source, a voltage drop of 2…8 % of the nominal operating voltage of the circuit can be approved. In the case of the test bench, it was chosen to use 3 % voltage drop in the calculations. This seems to be a small, meaningless distinction but when considering the voltage drop in a business and weight reduction point of view, it would play much bigger role when scaled up. Using thinner cables makes a big difference when the size of the batch is being for example vicinity of Volkswagen Golf.

As mentioned before, the nominal operation voltage of most devices on the test bench is 12 VDC, which means 0,36 VDC voltage drop for 3 %. When the current draw of any device is known the resistance caused by the voltage drop can be figured out. By using the equation (4) of the Ohm's law, the maximum resistance for a 12 VDC nominal operating voltage conductor is possible to calculate.

$$U = R * I \tag{4}$$

Which yields to

$$R = \frac{U}{I} \tag{5}$$

In the equation 4 and 5, the U is now the voltage drop of the conductor and I is the current flow. Now when the resistance of the conductor is known the CSA can be calculated by combining the equations 2 with 5 and in this way equation 7 below is achieved.

$$A = \frac{\rho * l}{R} \tag{7}$$

Which yields to

$$A = \frac{\rho * l * I}{U} \tag{8}$$

Here on the equation 8 the U is the maximum allowed voltage drop. In this way all the CSAs are being calculated and an example can be seen in the table (1) below. Since the test bench frame is relatively small, all the distances for wirings are rather short. In addition to that, many devices are consuming only a little amount of power and the currents are small as well. As the chart states, the minimum CSAs can be quite small, and that makes the wiring unpractical to use and more vulnerable to the mechanical stress and wearing. As mentioned earlier, the size of the production of the test bench is only one piece, so the cost of the wiring harnesses is moderate compared to all costs of the equipment installed. The amount of the conductor in meters for the whole bench is reasonable and for that reason the weight reduction was not something that needed to be taken into consideration. In the chart it is also listed on its own column what was the selected CSA of the example conductors of the test bench wiring harnesses. All the cables' conducting material is copper and the insulation material is polyvinyl chloride which is perhaps the most widely used material for electric cables due to its excellent insulating properties.

Table 1. An example of power and ground conductors' CSA calculated and used for a Robosense lidar unit and touch encoder interface.

Conductor name	**Current [A]**	**Length [m]**	**CSA [mm²] calc.**	**CSA [mm²] used**	**Fuse [A]**	**Color**
RSFr.PWR	3	7,4	0,38	0,5	ATO 2	Red
TEHI.PWR	0,13	2,0	0,01	0,5	ATO 1	Red
PC.PWR	50	3,40	3,58	6,0	Midi 40	Red

In the table 1 above, an example for the CSA calculation results can be seen. The table also contains information about the conductor names and colours, current draw (information from the datasheet), measured lengths of the conductors, and the calculated CSA. For the calculation of the CSA equation 8 was used with 3 % acceptable voltage drop.

2.5 Short circuit protection

Designing and dimensioning the conductors is essential to provide a solid current carrying capacity and to make sure that the demanded voltage is available for the power consumers of any electrical apparatus. With the design of the wires, the designing of the protective devices of the circuits goes hand in hand. In the automotive industry the electric design should always also consider the protection of a circuit at least for the case of short circuits and overcurrent overloading of the circuit. Protecting the circuit is often executed with different kinds of circuit breakers. In the household electric, also residual-current circuit breakers are being used but these are not common in the DC low voltage applications. Local valid laws, standards, and regulations should always be studied and obeyed before the design or installation of the electrics. This applies especially when a type of approval of the electrics for any commercial device are concerned. On the test bench's case only an automotive compatible circuit breakers were used.

When determining a proper circuit breaker, the essential feature of it is the protection of the devices and the wirings of the circuit. To avoid the risk of a fire, the fuse needs to blow before the conductor melts, or any potentially expensive device breaks due to overcurrent situation. In the field of automotive electronics, the type of fuses that are being used are thermal tripping types. They are less sensitive to blow and need higher load and warming before cutting the current of the circuit. In other words, they tolerate a bit more current fluctuation and overcurrent that may occur for example during starting or powering up a strong electric motor. (Juhala & Others 2005; 258-259.)

The basic principle for the fuse calculation is that the nominal current of the circuit is acting as a starting point. Both the conductor and the fuse should be able to handle the nominal amount of current for extended periods of time in the normal operation conditions. This means that the fuse voltage rating must of course match the operating voltage of the device and the ampere rating of the fuse is usually close to the nominal current draw of the device. For every fuse model family there are time – current characteristic curves available on the datasheet. From these diagrams, the necessary information about the relationship between time and current carrying limit for any fuse rating of the family can be found. By observing this chart, it is possible to make sure that the fuse will not trip for the nominal current of the circuit, and it is also possible to see how long the fuse will last in the case of overcurrent. (Linja-aho 2023.)

Now when a proper fuse for a circuit has been defined, the thermal constrains of the conductor must be considered. For this purpose, the time of thermal constraints of conductor (also t_c) is being calculated by equation 9 below.

$$t_c = \frac{k^2 * A^2}{I_{sc}} \quad (9)$$

In the equation 9, the k remains constant depending on the insulating material of the conductor, A is the CSA of the circuit and I_{sc} is the minimum short-circuit current. (Calculation of the minimum levels of short-circuit current 2022.) In the case of the test bench, the short circuit current is a bit tricky to determine. The power supplies are provided with a short-circuit protection, which means that demanded current is being produced until the point when a faulty behaviour e.g., short-circuiting or overload is being identified. When this kind of behaviour is detected, the current is either limited to the set maximum level or cut off in a harsh overcurrent situation. In this sense there should not be a chance of short-circuit at all. As described earlier, the continuous maximum current output for both PSUs is 60 A each. However, there might be a case in the future when the bench is being powered with a lead acid car battery, and in that perspective, the minimum short-circuit current should be taken from the battery specification. Short-circuit current is battery specific quantity depending on the contact surface between the lead material and the electrolyte, plate spacing, and separator materials which affects mainly to the internal resistance of the battery (Juhala & Others 2005: 27). Internal resistance sets and limits the short-circuit current based to the Ohm’s law.

One important specific of a lead acid battery is the low-temperature test current, which is often called as cold cranking amperes. It describes how much current the 12 V battery is able to produce in the temperature of -18 C when the engine is being cranked for 10 seconds, and while cranking the terminal voltage must not drop lower than 7,5 V. (Bosch Automotive Electrics and Automotive Electronics 2007: 422.) In the calculations, 300 A current for short-circuiting is used, which is rather standard cold cranking amps -reading for many lead acid starter batteries designed for passenger cars and small vans.

Now when the fuse has been chosen and it has been calculated how long the conductor, selected in the manner presented on the previous chapter, can handle the thermal stress, it can be made sure that the fuse melts before the conductor does. In other words, the breaking capacity (I_a) of the fuse must be lower than the breaking capacity of the conductor. As mentioned, fuse models have a datasheet that contain a chart for the time-current-characteristic-curves for each fuse in the particular “fuse family”. By studying the chart and comparing it to the calculations about the thermal constraints of the conductor the tripping of the fuse before damaging the wire can be ensured.

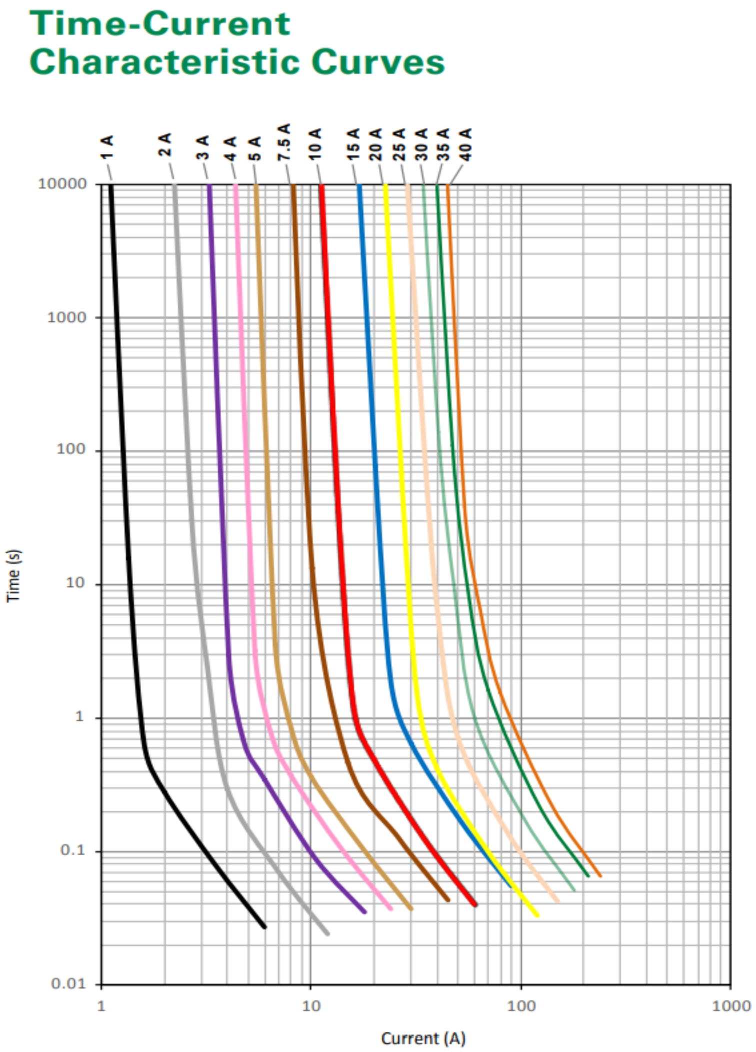

Figure 6. Time-Current Characteristic Curves (ATO Blade Fuses Datasheet 2022).

The picture above is a curve chart for a ATO Blade fuses. The chart presents logarithmic scale on both axes. As an example, if the nominal current of the circuit is 10 A, minimum short-circuit or overload current is 50 A and t_c is 2,0 s it can be noticed that a fuse with rating 10 A, 15 A, 20 A and even 25 A would fit this purpose. 30 A fuse and bigger ones would stand more than 2,0 s of the load which would cause damage to the conductor with 2,0 s t_c-rating. On the other side 7,5 A fuse would last around 10 s the nominal 10 A current before tripping.

In addition to the chart, every fuse has also I^2t value which indicates the available thermal energy resulting from the current flow. It includes melting I^2t that stands for the energy needed to melt the fuse, arching I^2t for the thermal energy passing by the fuse and total clearing I^2t which is the two first terms added together. These have two significant applications for determining the pulse cycle withstand capability and for choosing the right kind of fuses in a selectivity point of view that will be discussed later. The calculation of the I^2t is dependent of knowing the waveform of the pulses passing through the fuses. In the case of the short-circuit, the waveform can be considered to resemble a square form and the calculation can be done. Utilizing the mathematical model for finding out the thermal energy of the circuit during short-circuit and after that comparison to the selected fuse can be made. Fuse manufacturers usually reveal the I^2t total clearing and melting in the datasheets of the fuses. (Fuseology.)

As is the case in the test bench as well, the so called selectively coordinated fuse system is used. This means that on the power supply side there are couple of main fuses of several sub loads and on the load side of the circuit there are individual fuses for each consumer. The fuses must be selected in a way that if one of the consumers or its part of the circuit is short circuiting the load side fuse trips while the main fuse will last longer and keep feeding most of the sub systems. This can be achieved if the melting i2t of the supply side fuse is greater than the total clearing i2t of the load side fuse. (Fuseology.)

The pulse cycle withstand capability is also something to keep in mind when configuring the proper fuses. A fuse is under a mechanical stress while carrying current in a circuit, and this is the case especially when the current is pulsative. If the amount of arching i2t energy is great, the fuse will not last as long as it would with smaller amount of energy. This might affect to the lifespan of the fuse and should be under consideration with pulsative power consumers. (Fuseology.)

The external conditions are also affecting the life of a fuse. The current rating of the fuse is the maximum continuous current that the fuse can carry in a *specified* condition. In a room temperature of 25 °C the derating of the fuse should be set by 25 %. This means that the continuous current of the circuit should be 25 % less than the current rating of the fuse. If the ambient conditions are differing a lot from the room temperature, a rerating of the fuse should be adjusted by interpreting a specific rerating curve based on the voltage drop due to resistance changes at different temperatures. The rerated value can be calculated, but it will not be considered on this thesis since it is not affecting the test bench use cases.

The components and all the power consumers of the test bench are fused on the power side of the circuit. The PC is powering the cameras via ethernet cable and USB powered devices, and they are not fused as mentioned in the previous chapters. All the used fuses are automotive compatible, and their maximum rating for the voltage used is 32 Volts. For the calculations, the datasheets were studied, and when the information was not available, the previously made schematics of the Toyota Proaces were inspected. In the test bench, the earlier mentioned selectivity was applied. There are four main fuses in the fuse boxes located right next to the power supplies and the DC-DC converter. One of the main fuses is the only fuse for the PC and the remaining three fuses are supply side fuses for the load side smaller fuses.

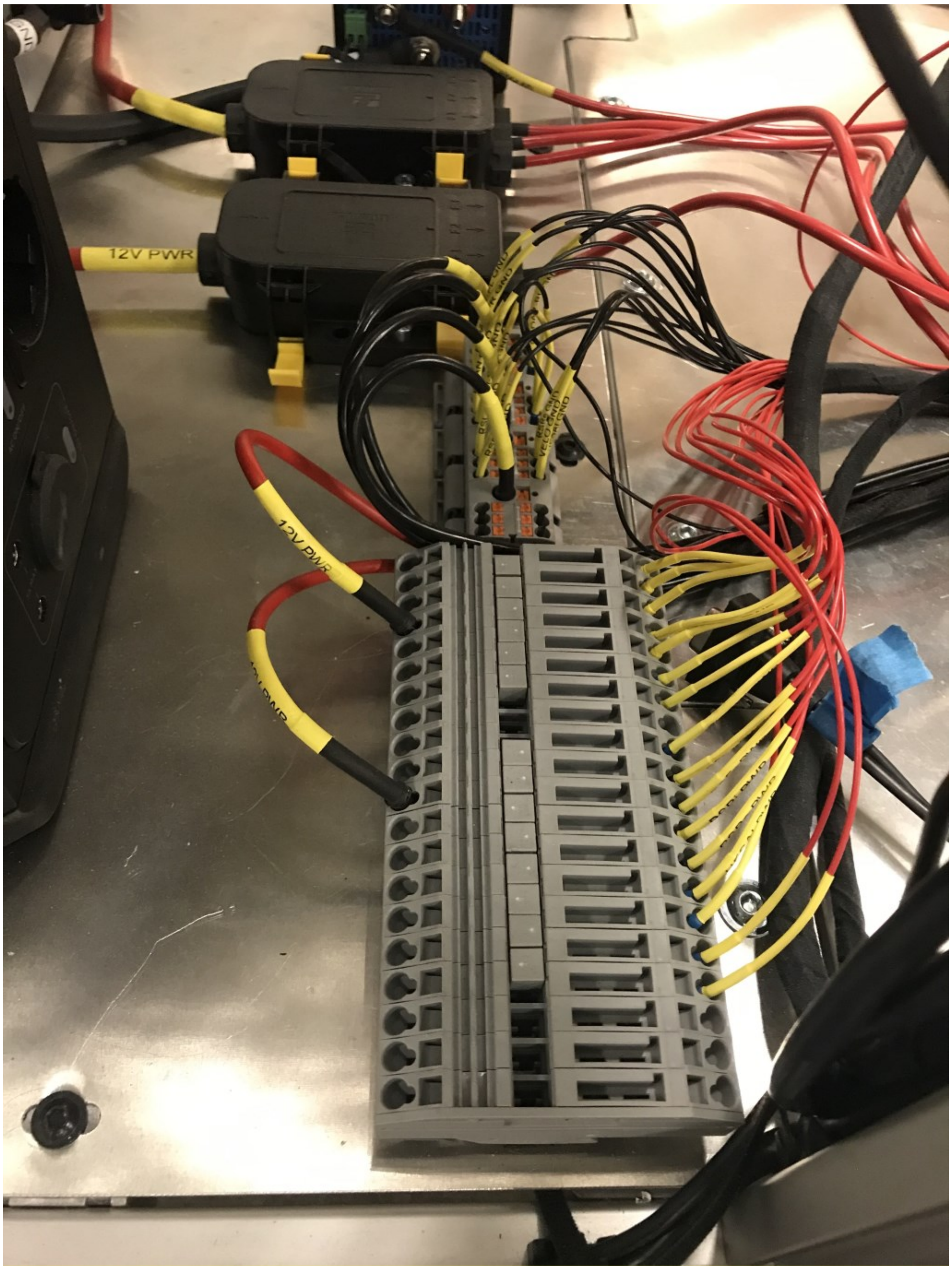

Figure 7. Test bench’s fuse holders.

In the picture above, the main fuses which act as the supply side fuses, are seated in the black fuse boxes. The fuse family for these main fuses is MIDI-fuse. The current rating examples are listed on the table (2) below. The load side fuses are familiar from the automotive field. The blade-style ATO/ATC/ATS/APR regular fuses are seated in grey fuse terminal blocks attached to the DIN-rail. Terminal blocks are handy, since the amount of them is easily adjustable and the power feed can be chained to several blocks with connecting parts. Terminal blocks are widely used on the automation technology field but are convenient in this application as well. They are modular for future additions and allow easy access to adjustment, if for example some devices are needed to turn completely off. The fuse ratings of all the fuses used on the test bench were calculated on the previously mentioned manner.

Table 2. Fuse calculations for two circuits.

Conductor / Component and nominal current [A]	Calculated CSA [mm^2]	Used CSA [mm^2]	Conductor t_c (60 A) [s]	Conductor t_c (300 A) [s]	Fuse curve (60 A) [s]	Fuse curve (300 A) [s]	Used fuse [A]
DC-DC to PC, max 45	3,58	10,00	367,4	14,7	100	0,3	MIDI 40
Robosense Lidar, 1,08	0,38	0,50	0,92	0,04	~0	~0	ATO 1

The table 2 above represents some of the initial figures needed for the fuse calculations and the CSA calculated results and the actual chosen conductor, which in these cases are much thicker than the minimum needed. It also represents the chosen fuse for two circuits for different devices. As these devices are consuming very little power the current flow is also tiny. Hence, small fuses are used and for those the tripping and opening the circuit will happen very fast. This leads to the designed behaviour where the fuses pop protecting the circuit before the conductor reaches the melting point or are even close to that.

3 Wiring and harnesses

3.1 Schematics

As the subject of this thesis is applied to test bench electrics, some designing was a mandatory step before any wiring could be assembled. The modelling of the schematics happened with KiCad software, which had been previously used in the company as the main tool for drawing the schematics. KiCad has many different editors including editors for printed circuit board designing but, in this case, only the schematic editor was needed.

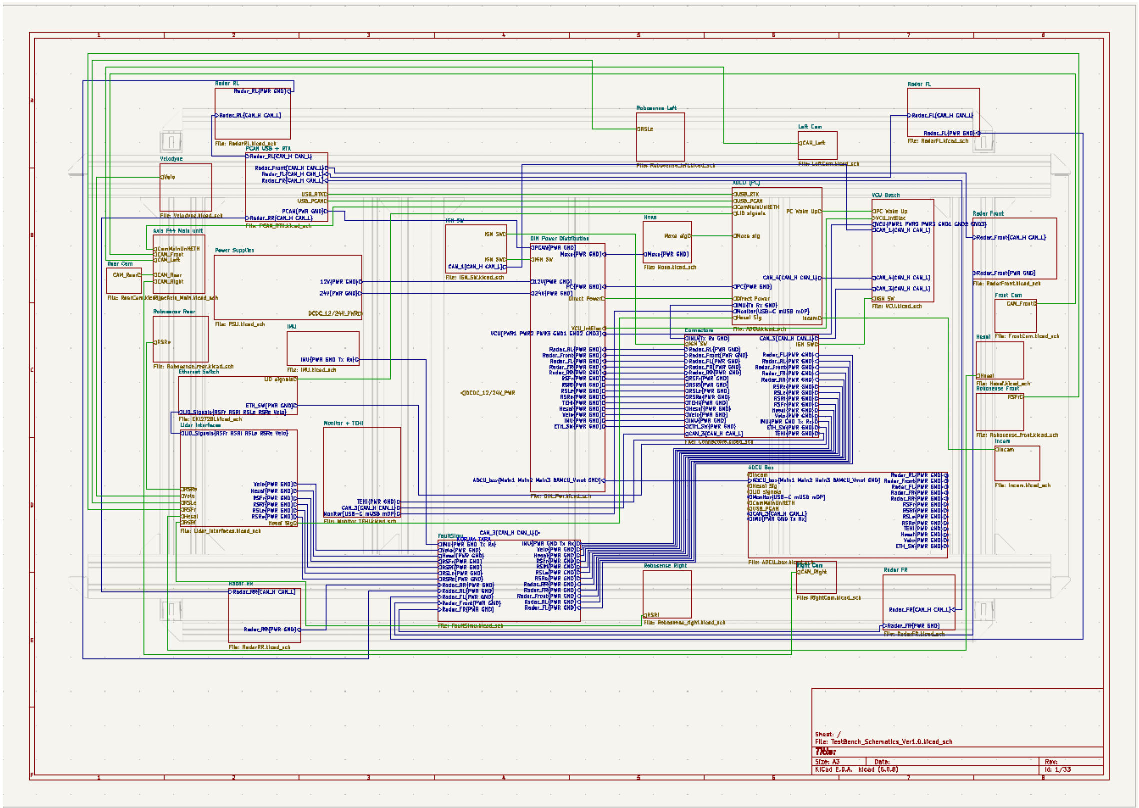

Figure 8. Kicad schematics front page with the test bench layout.

The picture above representing the front page of the schematics depicts the overall picture of the test bench including all the hierarchical sub-level sheets. With a first glance, the whole layout of the test bench can be seen from the top view. Since the test bench has three vertical physical levels (shelf would be more describing word for them) where the components are located, the top view cannot provide the exact places in 3D perspective. This is the case with all the schematic layouts, and for expressing the actual places for all the components a photograph of a 3D model works better.

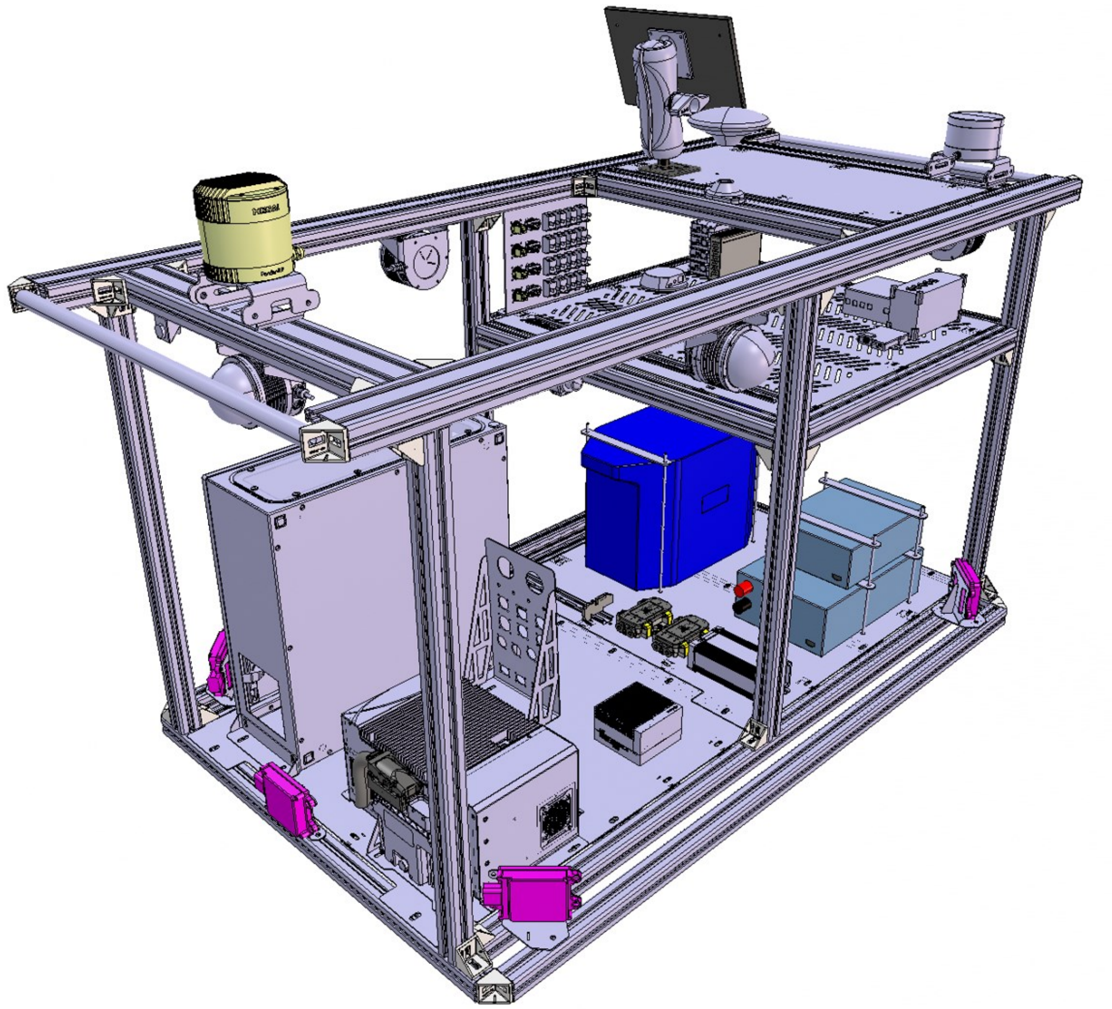

Figure 9. 3D-model of the test bench.

The layout is not presenting the components or all the wirings but instead it is a table of contents of a sort that takes the viewer to more precise details with only double clicking any of the hierarchical sheets. Inside of these sub-sheets, it is possible to see the actual components presented as “boxes with the necessary inputs and outputs”.

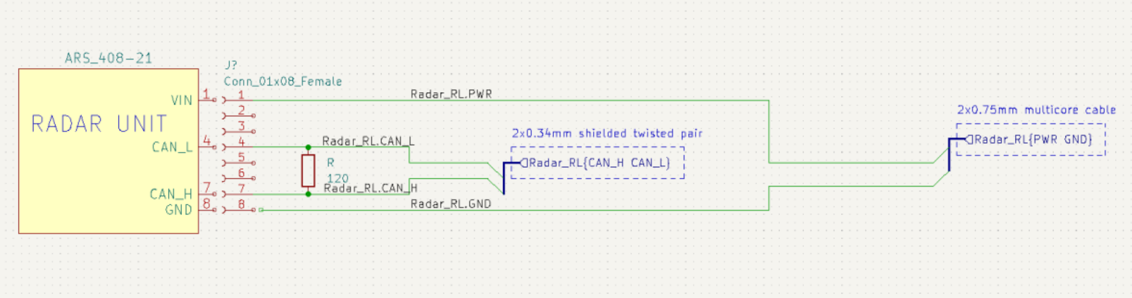

Figure 10. Kicad picture example of one component with pin outs illustrated.

KiCad’s schematic editor includes a huge library with various components. Nevertheless, it not perfect, and some components needed to be made from a scratch or edited from an existing one to illustrate better the components in the test bench. There is a useful component editor included on the Kicad where one can create a new or modify an existing component in endless ways. Many components were also found from the different Toyota Proace KiCad libraries, and they could be used in this project as well. Some modifications for the set up were needed, since the older libraries were from the KiCad 5, and schematics for the test bench were executed with a newer KiCad 6 software.

The wirings being either single conductors or busses are expanded in detail in these hierarchical sheets. The viewer is able to see how many conductors are needed for each component and for the additional information addressing for example the colours, CSA of the wires, and some additional information concerning the crimping or treatment for the cable shielding etc.

In the schematics, many of the conductors are represented as wiring harnesses wrapping up several conductors, and that is the case especially on the first layout page. By doing this, the overall picture will not be so messy, and the actual layout can be observed better. The harnesses on the schematics may, or may not be, the actual case with the bench when it comes to the physical layout of the conductors. All the details are not shown on the wiring diagram, but each conductor has its own name which corresponds to the name on diagram. In this way it is easy to follow the wires with the help of the schematics.

3.2 Conductors and harnesses

Manufacturing the conductors and integrating those as harnesses of several conductors was the most concrete part of the process. The hands-on section of the job included more precise measuring of the lengths of each conductor, although a rough estimation of the length was already made for the CSA calculations mentioned previously. Some of the estimates were quite close to the realistic lengths, and some needed more fine tuning. The ballpark figure was however close enough to specifying the right CSA for the conductors.

Planning the harness in a way that future modifications could be possible was something that needed to be considered all the time. The most challenging task when designing was the fact that several different computing units were supposed to be interchangeable with only switching couple of connectors from a place to another. The initial plan was to make the design so that “anybody” could do the switch with kind of a “plug-and-play” mentality. This was carried out by using a special connector plate that performs as a “physical control panel” for choosing which PC the tests are run with.

Figure 11. Test Bench Connection Panel being made.

In the picture above, the connector panel is presented with some of the needed connectors for the switch between different computing units. The biggest connectors are HD-series made by Deutsch and they are used for mostly powering the devices when running the bench with its own power distribution. The other option for powering the sensors is a ready-made AD-box similar to Toyota Proace boxes (picture 11) which has its own power distribution and fuses inside it for powering and protecting all the sensors and devices. This is also the significant difference between the two possibilities of using the bench. In the future, there will be also the Nvidia platform added in for testing, but it will have more or less the same kind of powering up manner for the devices as with the Vecow PC. More detailed wiring harnesses are made for the Nvidia when it is studied and installed to the test bench in the future.

Figure 12. Toyota Proace AD-box including the computing unit’s front cover with the connectors.

On the schematics, the interchangeability means that both ways which might be chosen to run the test bench with have to be presented. In practise, this means that in the front layout page there is hierarchical sheet for the Vecow PC and also for the AD-box.

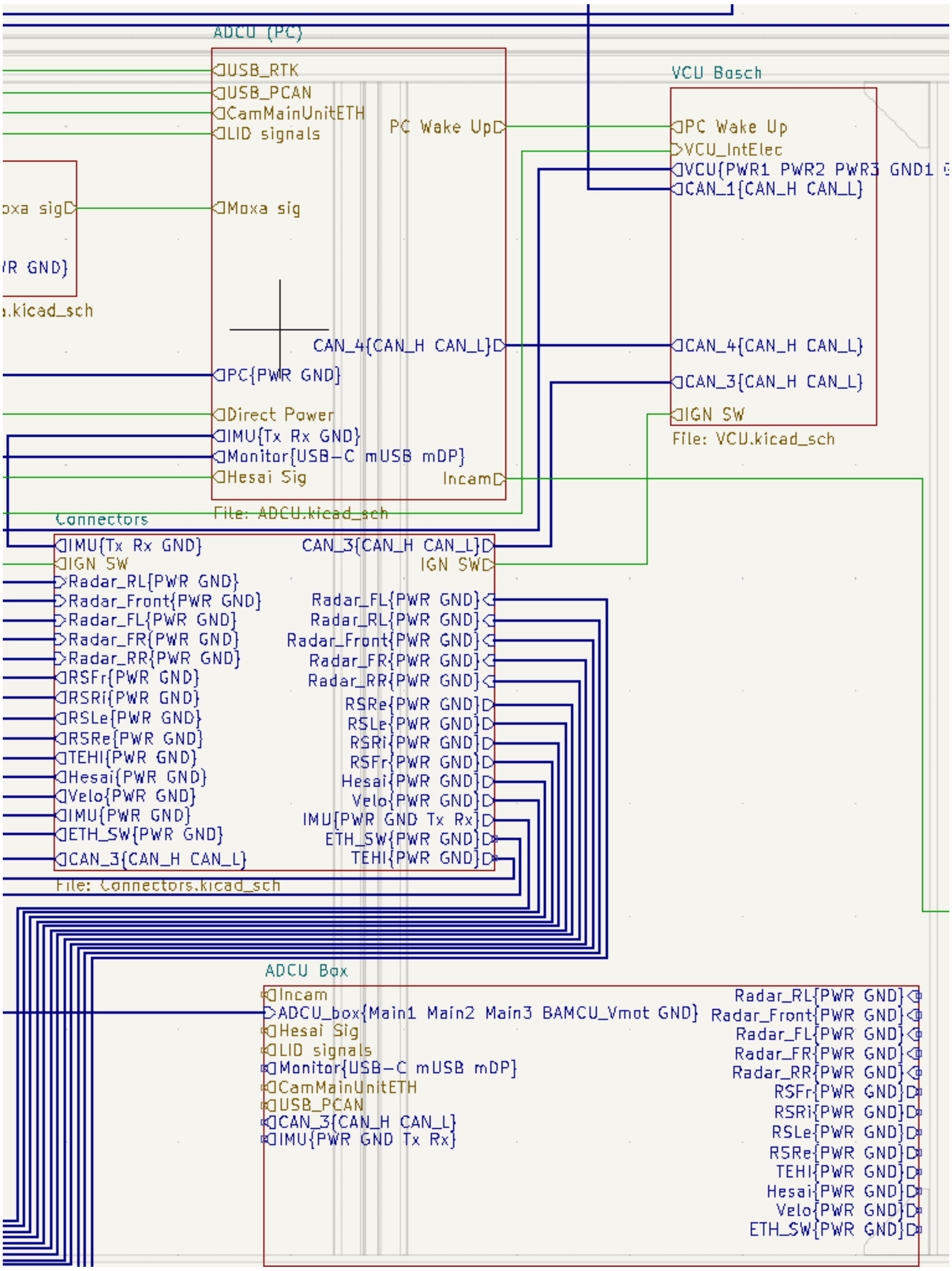

Figure 13. Kicad wiring diagram presenting two optional computing possibilities.

In the picture above, both hierarchical sheets are shown, and by clicking each one of the details of the connections and the connectors including buses can be illustrated clearly. Something worth noticing is that only one set of wiring is drawn into the schematics. It was chosen that the conductors will be illustrated in a manner that the computing unit is the bench's steady mounted Vecow PC. The conductors could have been drawn to both computing units but it was decided not to do it in sense of making the schematics as illustrative and clear as possible.

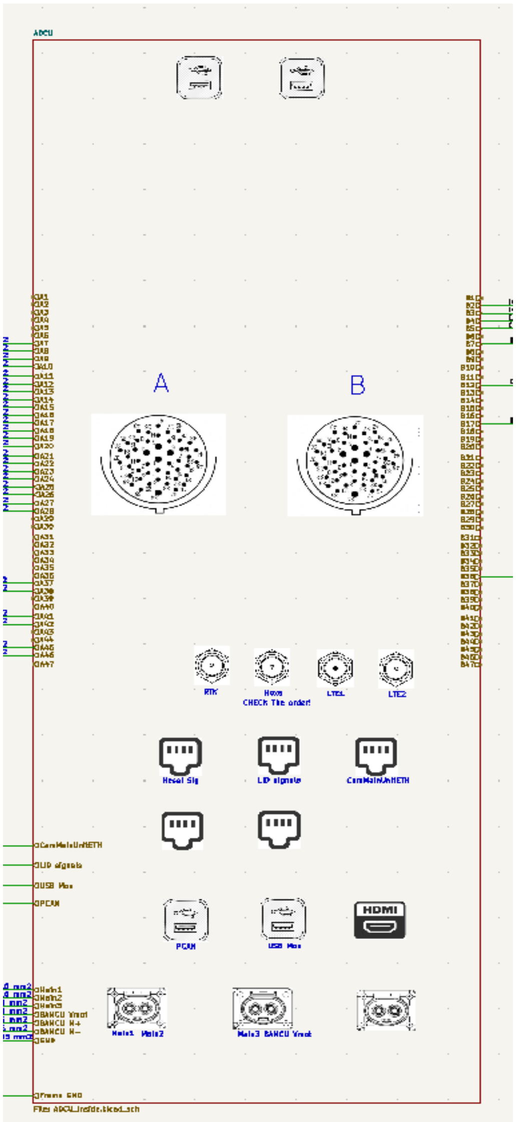

Figure 14. Kicad schematic illustrating AD-box as a component with the connectors on the front panel.

4 Fault simulations

For testing purposes, it was clear from the beginning of the project that some possible electrical faults and symptoms must be able to be fed into the AD-system of the test bench. The Sensible 4 system team was consulted for this part, since they have the best overview for the whole architecture, and they have history for tackling the faults of the AD-system. Some request that the system team provided were:

- Possibility to power out any AD-sensor one at the time.
- Possibility to feed corrupted CAN-messages to the CAN-buses of the test bench.
- Possibility to feed corrupted data to the ethernet bus.

With these features, it is possible to simulate some experienced and new fault situations, and from a testing point of view it is beneficial to learn from these in a test bench rather than on the site with customer projects. Preventing and fixing bugs plus other issues in advance is one important aspect that the testing is aiming at. The cost of a bug fix on a released software is multiple compared to the fix that is being made on the developing phase and very much time consuming as well. From a customer service perspective, a neatly working product is always something to aim for.

4.1 Powering out the sensors

For the test bench, the user interface for powering out any sensor could be solved in many fancy ways, but the immutable aspect in every possibility is that the current flow needs to be cut or lead to someplace else. In this case, simple switches were used in a straightforward manner. This was possible because there are not too many sensors which need to be taken out, also considering the fact that the current for powering up these sensors is not too strong. If the current would be significantly higher, the switching might cause sparking at the contactors of the switch. Also, the transient moment of the switching on and off didn’t cause any currents or voltages that were considered to be harmful for the circuit. This was also proven to be true by using oscilloscope to measure the voltage and current peaks on the time the power was cut.

Figure 15. Voltage and current measurement while powering out a lidar sensor.

The current peak when a Robosense lidar sensor is being powered off is illustrated in the figure 15 above. It is a screen shot from the Pico scope oscilloscope where the current draw (red) and the voltage (blue) of a power feed is being logged. Current peaks approximately at 5 A and hence cannot be considered to be harmful for the interface. The setup for the experiment was carried out by cutting the power feed from a conductor powering the interface while the interface is powering the sensor as described earlier. The measurement was taken from the power feed of the interface which means that during the experiment only the condition of the interface can be known for sure. If the current peak and the voltage behaviour of the power feed to the sensor is the subject of investigation the measurements should be done from the power feed and ground conductors between the interface and the sensor. This measurement was not conducted since it would have required compromising the OEM conductors of the sensor. The wirings were kept untouched to prevent any other misbehaviours of the sensor. Cutting the cable requires for fixing it after the measurement have been done by soldering it of by using connectors.

Due to bad contacts caused by the mechanical stress and corrosion of the connectors, voltage drops may occur at some point of the lifespan of the test bench. Also, the 5 A current peak towards the interface suggest that any radical peaks disturbing the sensor are most likely not happening.

The switches for disconnecting the power for any sensor are located near the screen of the bench, so they are easy to use and simultaneously monitor the changes in the data output and in the software running. A specially designed swich mounting place for this case pictured below was used. The amount of the switches is over scaled for the number of sensors at the time but it is useful to include some spare switches for the future additions and modifications. The same plate also includes connectors for entering the CAN-bus and the Ethernet connection. In a wiring point of view, routing the power feed of all the sensors makes the conductors longer and the routes for the harnesses being used are more packed with wirings. The increased length of the conductors must be considered when calculating the CSA for each conductor and some planning where to route the harnesses has to be added but other than that the addition is very simple.

The switches are typical on/off switches. When choosing these components, a special attention was paid towards the current withstand, the contactors, and the overall looks to fit the purpose. The switches have a feature for shutting off two circuits if the disconnection is needed to be done for two sensors from a different circuit at the same time. At this stage, shutting off only one sensor at the time was enough but for the future modifications this could turn out to be a handy feature without any additional costs. Switches for two circuits are equally priced as for one circuit. Also, if needed in the future, several sensors can be switched off from a single switch with a small number of new wirings to be installed routing the circuits via one of the unused switches.

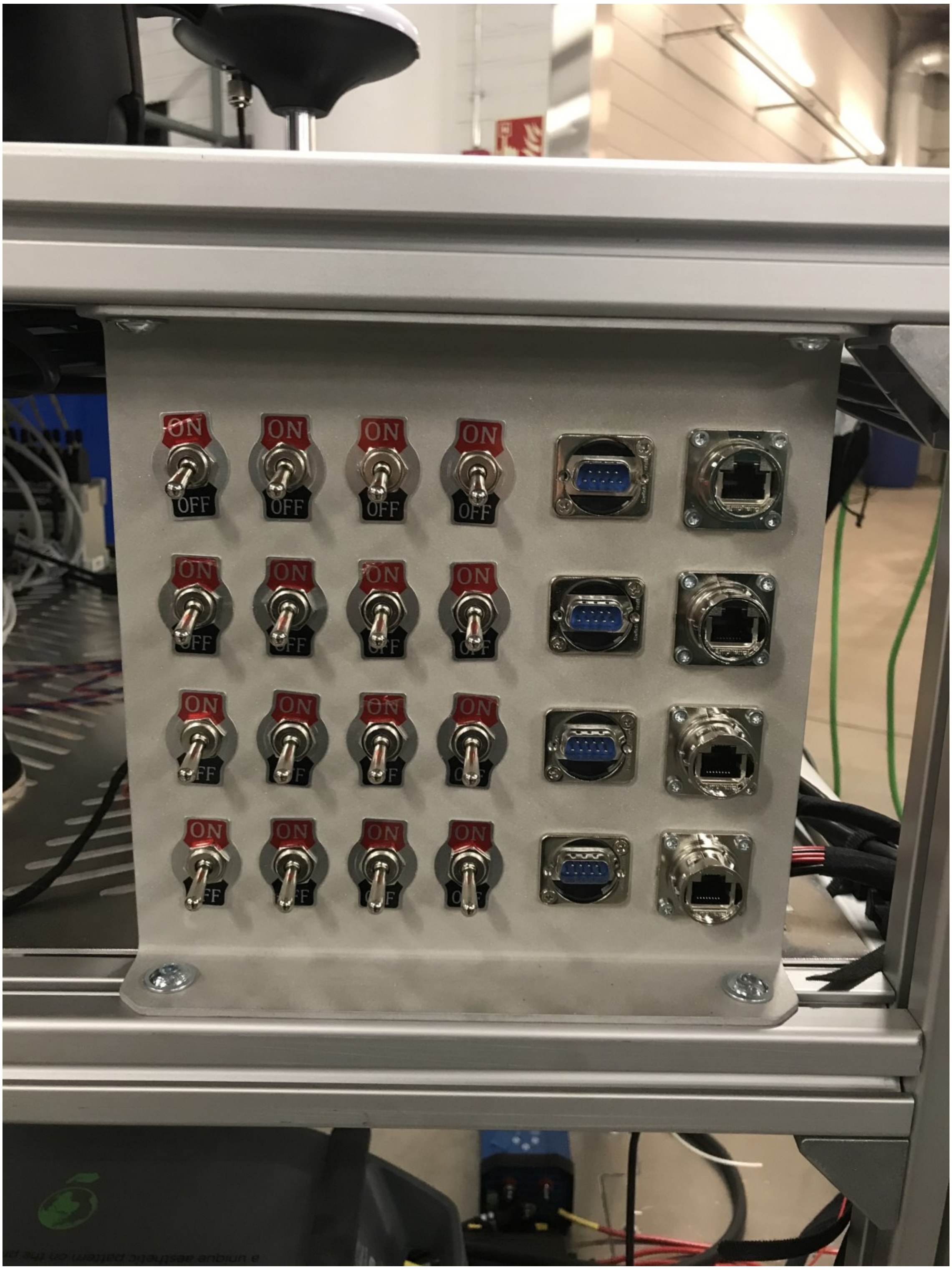

Figure 16. Switch Plate for the fault simulations.

4.2 CAN-bus fault simulations

As previously mentioned, the CAN-bus fault simulations were requested to be included for a possibility to feed corrupted CAN frames to the bus. The CAN frame is one message sent from a control unit to another including the actual message and all the other needed information for example concerning the urgency of the message and the receiver for whom the message is appointed to.

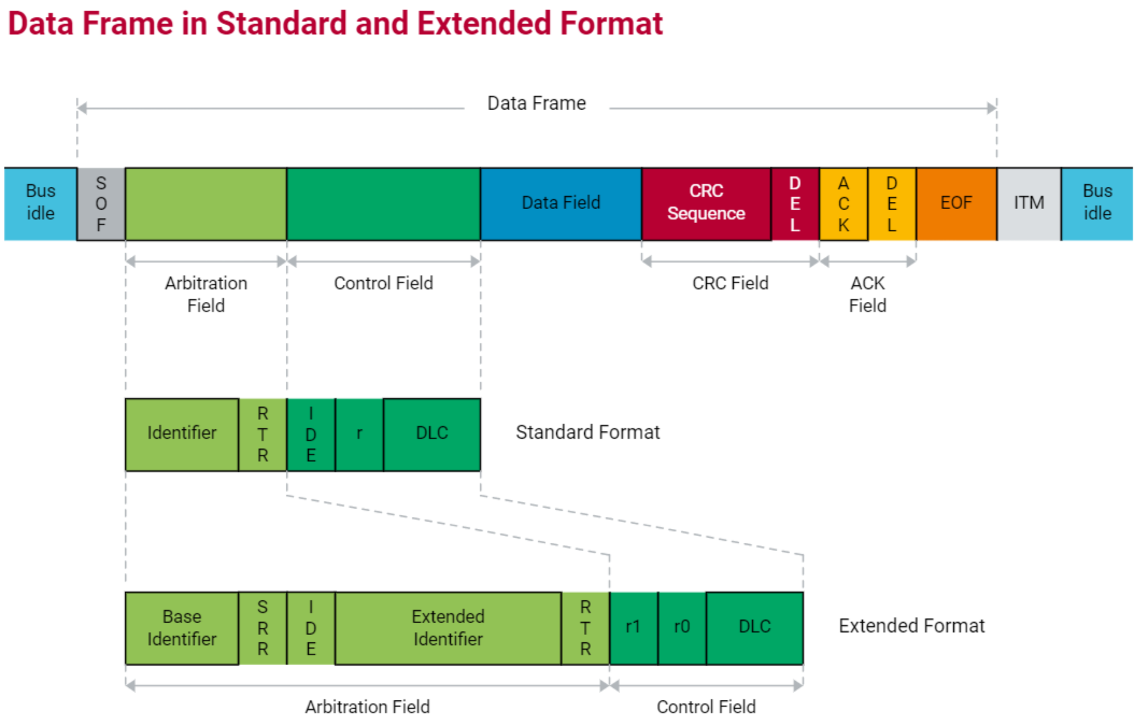

Figure 17. CAN frame (vector.com).

In a standard CAN frame, there is 11-bit identifier after a 1-bit Start of Frame that is included in all CAN frames. The identifier can also be 29-bit in the extended CAN frame. This enables more different identifiers to be used for multiple control units in the same CAN bus. The identifier also includes the priority information for taking over the bus when two frames are sent exactly the same time. A CAN message can be also requesting information from another device and that is the purpose for Remote Transmission Request bit followed by Identifier Extension bit for providing the info whether the frame is being extended or not. Before the actual message in the CAN frame, there is also 4 bits for the expressing the length of the data being sent and r0 for future use. All these bits after the identifier are often referred as the control field. The data being the beef of the whole frame is maximum 8 bytes. After the data there is received space for checking the validity of the message and it is called Cyclic Redundancy Check that is taking 16 bits. If everything is ok, the receiving device sends a message in the Acknowledgement bits in the same frame and an End of Frame is followed. After the next message, there is also some blank space before next frame is sent. (Frei 2015: 12; Data Frame 2021.)

There are couple of different kinds of errors that could occur in the CAN protocol. First, the acknowledgement bit can cause an error if it has not been set off by the receiver. There can also be an error with the CRC part of the CAN frame where the receiver is performing a checksum algorithm comparing the result with the received result of the checksum. If it matches, the frame is received correctly. If it does not match an error frame is sent to the bus after the acknowledgement bits. The error can also be on the end of the CAN frame where the protocol sets the acknowledgement always to be recessive bits and the end of frame to be also recessive bits. If any of these are dominant bits caused for example by electromagnetic interference an error is spotted. Error can also be spotted already when it is being sent by the sender itself. The transmitter/receiver of the control unit is monitoring the message all the time, and if any inconsistencies are spotted, the transmitter cuts the sending and starts it all over again from the beginning. Also, in the CAN protocol it has been set that no more than five similar bits in a row can follow each other excluding the ending of the message as previously mentioned. If for example six dominant bit are noticed in a row an error flag will rise. (Frei 2015: 24-26.)

As the bits on both CAN conductors should be either recessive or dominant, the possible error is easy to spot for a computer. In the physical CAN conductors, recessive and dominant bits are expressed as certain volt levels depending on is the bus high-speed CAN or low-speed CAN. The receiving units tolerate a small error in these levels, however, the levels should be in the ballpark figure to make the difference calculated from the difference of the CAN-high and CAN-low volt levels clear to express the logical dominant or the logical recessive state of the bit.

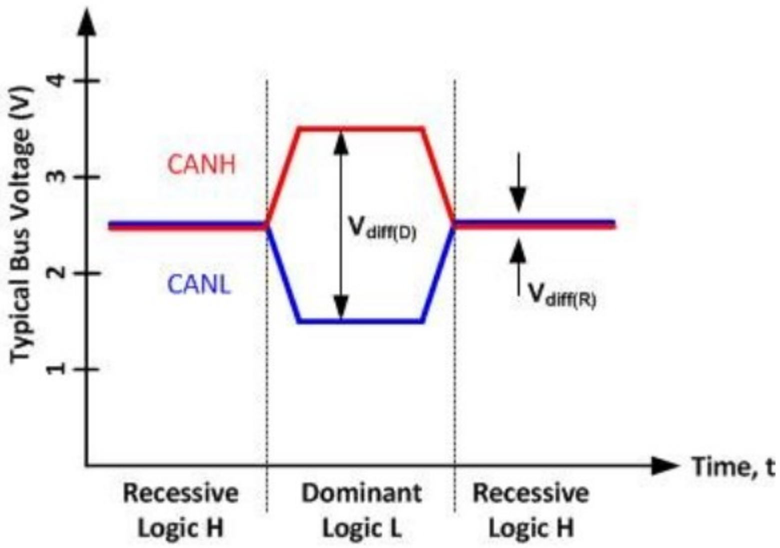

Figure 18. High-speed CAN-bus differential signal (e2e.ti.com).

The physical robustness and redundancy are achieved in the modern CAN-buses with the twisted pair wiring. This means that the conductor of a low-speed and a high-speed CAN is consisting of so-called CAN-high and CAN-low wires that are twisted together. Twisting the conductors together improves the electromagnetic compatibility of the system a great deal. The robustness of the system comes with the two conductors transmitting a differential signal. The signal bits are complementary to each other and, therefore, the same transmitted message is travelling as a mirror image in the two CAN conductors. The receiving control unit is comparing and calculating the signal and now it has two sources for the same message. If any errors due to electromagnetic conditions occur on the one conductor, it also affects the other conductor as well. The receiving control unit is calculating the sum of the differential signal and based on the speed of the CAN-bus and CAN protocol it is known what the difference between the CAN-high and CAN-low should be, when the logical state is 1 or 0. The same kind of error caused by electromagnetic interference on the conductors will be summed out because the difference of the signals remains the same.

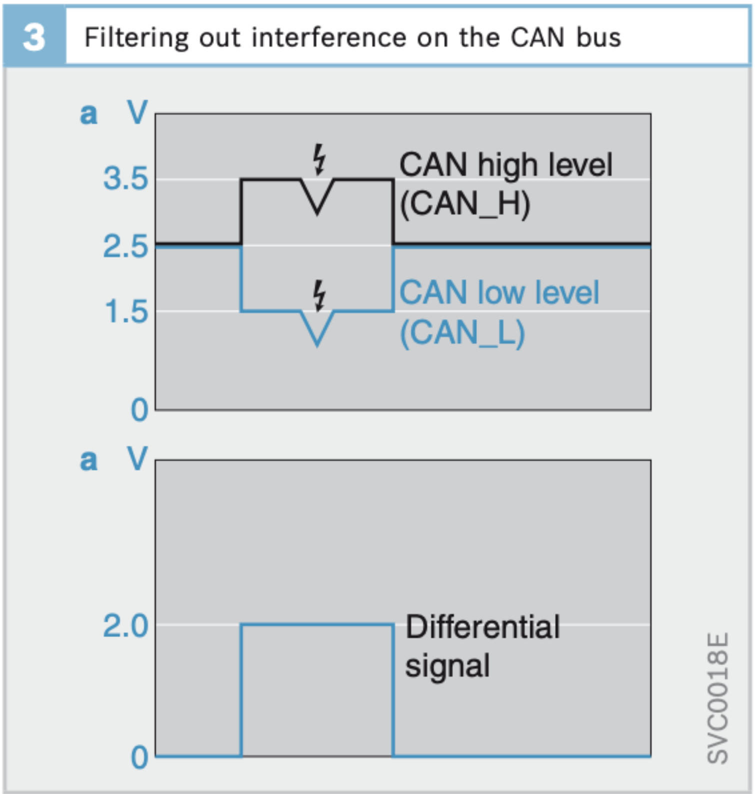

Figure 19. CAN Differential signal summing out the error (Bosch Automotive Electrics and Automotive Electronics 2005: 94).

In the main use case of the test bench, the corrupted CAN frames are injected to the bus. These frames are “handmade” with CAN software tools, and the possibilities of the modifications made to the data load are almost unlimited. While the before known errors injected to the different buses of the bench will be the main use case also an electromagnetic interference can also be applied. Any magnetic sources such as electric motors can be “manually” brought to the proximity of the CAN-bus conductors and the results can be seen on the output data logged by a CAN logging tool or from the AD-software. As explained above, the CAN signal is able to handle some amount of interference but surely the error frames can be formed if the magnetic source is strong and close enough to interfere the normal signal transmission.

To inject CAN frames to the bus, a physical connection is needed for a message sending device to be part of the bus, acting as any other node in the system. For this purpose, a DB9 connector was placed on the same switch plate where the previously mentioned on/off switched are located. The connector is easily accessible and widely used and approved by many third-party CAN interfaces which Sensible 4 is also using. On the Toyota Proaces there is similar DB9 junction on one of the CAN buses for diagnostics and flashing purposes.

Figure 20. PCAN-USB CAN interface (Peak-system.com).

There are many physical CAN interfaces on the market. One widely used is PEAK System’s PCAN-USB that the company is also using. It has DB9 connector on the bus end of the device and a regular USB-connector to the computer end. A laptop, or such computer, is being used for the CAN software, of which there are numerous on the market. PEAK System also have several software tools of their own for any kind of configuring, tweaking, plotting, or reading the CAN messages. Since the CAN fault simulations are not the primary subject of this thesis it will be not covered further here.

4.3 Injecting faults into ethernet

The word ethernet stands for a family of wired computer networking technologies and it was standardised already 1983, although the Internet for wide public and commercial use was making its way for ten more years. The standard includes multiple wiring variants, but the ones being used nowadays are twisted pair and optic fibres. The ethernet is widely used technology and it has also become inseparable part of the modern society and lately also vehicles' communication protocols. (Wesley 2021.)

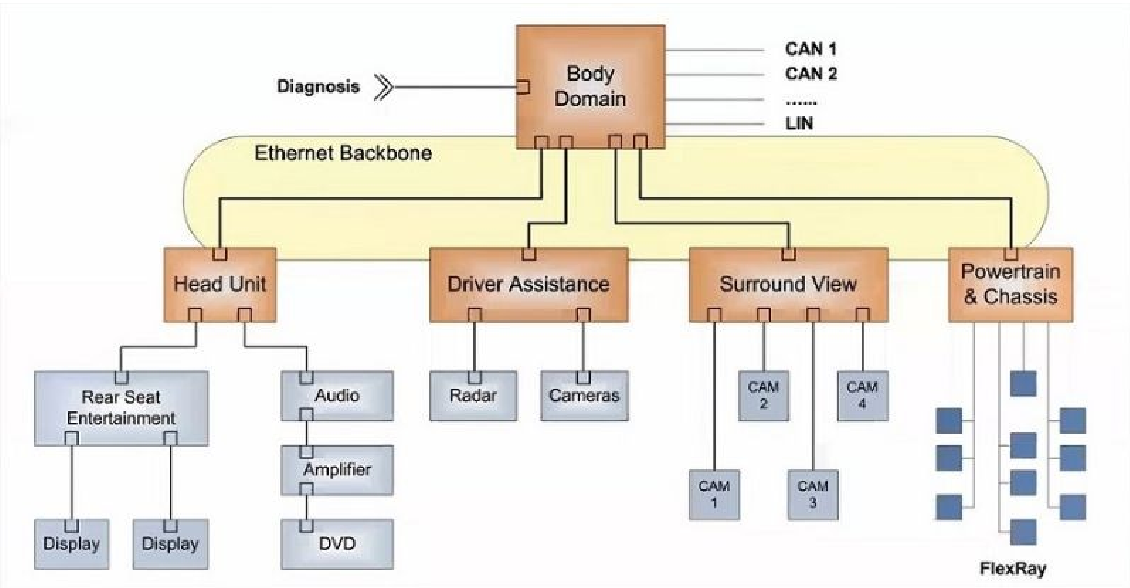

Figure 21. The ethernet as a backbone architecture of the vehicle network (Lim 2021).

The messaging via ethernet connections reminds considerably the communication that happens in the CAN-bus. Both of these communication technologies split the stream of data to the shorter packets called frames, and as the same way it is in the CAN-bus, ethernet includes the destination addresses and error checking data besides the actual message in each frame.

Ethernet technology allows much faster communication than CAN and also, the need for speed is remarkable when one decides to use ethernet communications. Compared to the CAN, the amount of data that needed to be transmitted is enormous, taking the live video on the Internet as an example. The ethernet switches being used also on the test bench makes the ethernet bus uncrowded and collision free and provides the possibility to use different ethernet protocols with different speeds on the same network. The nodes on the bus does not have to compete for the same cable since the switches are handling the communication in a way that it is the most efficient. (Wesley 2021.)

CAN-bus used on the vehicles is fast enough to meet most of the needs set for the vehicle communications. The current improvements e.g., CAN FD (flexible data rate) makes the CAN-bus more up to date, as the amount of the data increases all the time. However, the ethernet can be found from a modern car as one part of the network system architecture. Ethernet and the fast bit rates of it are used on the ADAS systems with cameras and lidars, and also diagnostics over Internet protocol (DoIP) provide a possibility for remote software updates, diagnostics and data logging. (Solutions for Automotive Ethernet.)

As mentioned on the previous chapters, there are couple of ethernet connections on the test bench. In the fault simulating perspective, the ethernet connections of the lidars are the ones needed to be entered and manipulated. The data of the lidars are either routed via the ethernet switch or directly to the AD-computer as is the case with one lidar model. Fault injection into the ethernet is carried out in the same manner as with the CAN-bus being the case. The ethernet standard RJ45 connector for entering the ethernet bus is located on the same switch plate where all the other fault simulations can be executed. From this physical interface the connection and the feed of the corrupted data can be conveyed with an ethernet cable and a computer. For the reading and writing of the data a software for the computer is needed. There are several options available on the market for that purpose.

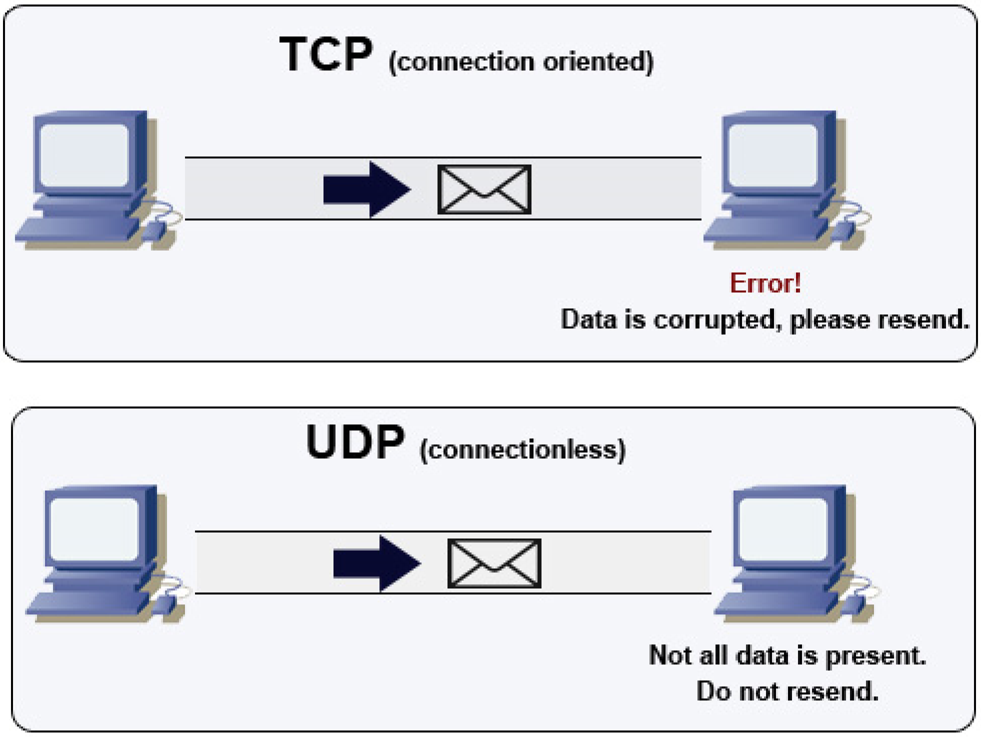

Figure 22. TCP protocol versus UDP protocol (Compare and Contrast the advantages and disadvantages of TCP – UDP).

The lidars of the test bench are communicating using User Datagram Protocol (UDP) on the top of the Internet Protocol. It is commonly used protocol on the applications like this where a huge amount of data is flowing very rapidly, and the errors are not being handled on the spot to make the speed of the data flow better. The speed of the ethernet must be able to reach 100 Mbps providing approximately 600000 points per second. (RS-Bpearl User Manual 2020.) When comparing this ethernet data speed and amount to the CAN-bus data the difference is remarkable. For handling the data, a software tool for that purpose is needed, and for example widely used programming and numeric computing platform Matlab is providing UDP interface tool for managing the data communication (UDP Interface). As ethernet technology, telecommunications, or data processing are not the subjects of this thesis, the further details of these technologies have been left out.

5 Results and conclusions

Due to some company in-house concerns that were not related to the thesis, the test bench was not fully ready by the time this thesis was completed. The electric assembly was thus not completely finished and it resulted in not finishing the testing part of the electrics. Nevertheless, the electric design was fully completed, and some revisions with improvements were also made to make the final product to correspond better to the set targets and make the test bench better.

Although the final physical product was only about 80 % finished, and the testing part will be made in the future, it can be stated that the test bench reached the goals that were discussed in the previous sections of this thesis. The electric design and implementation were conducted in a straightforward manner, keeping in mind all the requirements and the overall purpose of the device in the first place. The modularity and future additions were considered in every step of the project keeping in mind the budget limits, physical constraints, and the restrictions set by the mechanical and the electrical hardware that were already planned and purchased.

The schematics that were made using KiCad software were also documented for the company's use. Although the schematic diagrams were mainly completed for the designing of the electrics, they can be used as a guideline if some repairs or modifications are needed later. It is convenient to follow any circuit using the wiring diagram that has the layout on the front page to see at a glance all the necessary connections between the different devices. The components located on the schematics' front page are in the diagram where they have been mounted on the real bench as well, which makes the fault finding and perceiving the big picture easier for somebody who is not that familiar with the case. When it comes to the drafting of the schematics it could have been a welcomed feature and some addition to the project to use a wiring harness software specially made for that purpose. Although, making the schematics from a scratch was a completely new experience for me and it did challenge me a great deal, the wiring harness software would have been also a fantastic learning experience on the top of the electrical design.

One concrete surprise for me included the physical dimensions of the bench. Although the bench is quite big and from the first glance the amount of space for the wirings, fuse holders, etc. seem to be more than sufficient but in the end, there were not that much loose space as one could have thought in the first place. Some harnesses, and maybe even the components, could have been located differently for the sake of the space and possibly future additions but on the other hand, the bench works, and the routes for conductors being used are short and functional. Further additions of components and the required wirings can be fairly easily made but perhaps the aesthetic look will suffer a bit from the additional elements included to the bench.

The mechanical and electrical layout of the bench can be justified and declared to be successful, and the bench is fulfilling the purpose. Nevertheless, there were some aspects that did not work as well on the spot as they did “on the paper”. Some concerns were caused by the fact that the pricy 50000+ € project did not have a clear project manager who would have had the last say in how different matters should be handled. There were some moments of uncertainty where a project leader could have been the person to turn to for the answers. On my perspective, the integration of the mechanical side and the electrics is the part where the project manager would have been needed. On the other hand, all the supervisors of this thesis and the fellow workers of the company helped me a lot and I have only good experiences regarding their sincere willingness to help me with every detail of my work. It was also an enormous learning experience for me to make some decisions by myself and trust my abilities for pushing my part of the project through. I want to thank everyone involved this project and the thesis for the great output and my supervisors for giving me the responsibility and the chance for learning all the new skills.

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