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Electronics Development of a Formula Type Steering Wheel

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Abstract

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The purpose of this thesis work was development of a circuit board for a new steering wheel design for Metropolia Motorsport, built on an earlier prototype made by Metropolia Motorsport. The circuit board has Bluetooth Low Energy wireless functionality, is battery powered, supports being wired with up to four buttons, two potentiometers and one joystick, and is able to display data on an OLED display.

The design process generated two boards, one for development and initial validation use, and the second one being a finished design meant to be mounted on the steering wheel. Both boards were made using KiCAD for circuit board development and programmed using the nRF5 Software Development Kit. Both boards were assembled by hand from ordered components.

The result of this work has been successful. Although some improvements could be made, the core required functions of the steering wheel work as requested by Metropolia Motorsport, and preliminary measurements and tests have been promising. The circuit board has at the time of writing not been tested with an actual vehicle nor been fit to a steering wheel, but that is expected to be done some time between summer and autumn.

Overall, the project has been a success, and the board or a revision of it will be used in Metropolia Motorsport cars in the future.

Keywords: BLE, Bluetooth, Formula Student, Wireless, Battery, Portable, Electronics

Contents

List of Abbreviations

4WD: Four Wheel Drive.

ADC: Analog to Digital Converter

FFC: Flat Flex Cable.

IC: Integrated Circuit.

IDE: Integrated Development Environment

PCB: Printed Circuit Board.

PPM: Parts Per Million

REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals.

RoHS: Restriction of Hazardous Substances Directive.

SPI: Serial Peripheral Interface.

UUID: Universal Unique Identifier

VCC: Voltage Common Collector

Glossary

0603: One of the standard resistor and capacitor sizes defined in IEC 60384-22 and IEC 60115-8.

BGA: Ball Grid Array. A type of electronic chip package made to be soldered with a grid of small soldering tin balls under itself.

BLE: Bluetooth Low Energy. A wireless protocol created and defined by the Bluetooth Special Interest Group, made for low powered wireless applications.

E12: One of the E series of resistors defined in IEC 60063 having 12 values per decade and having 10% tolerance values.

ECU: Electronic Control Unit. The main control unit controlling a vehicles motors and sensors.

I2C/TWI: Inter-Integrated Circuit/Two Wire Interface. A serial communications interface commonly used in digital electronics.

OLED: Organic Light Emitting Diode. This is a type of display technology commonly used for higher end televisions and monitors, as well as smaller displays requiring good viewing angles and strong lighting.

QFN: Quad Flat No-lead package. A type of electronic chip package with no soldering legs and commonly with a thermal pad underneath itself.

SoC: System on a Chip. This describes an electronic chip, typically a microcontroller or microprocessor, which includes additional features such as a built-in radio transceiver or graphics processing unit.

1 Introduction

As technology progresses and new developments are made in formula student vehicle design, there is more data and information than ever before for drivers and engineers to digest and fine tune to achieve better performance and faster speeds. Figure 1 shows a render of a modern Formula Student vehicle.

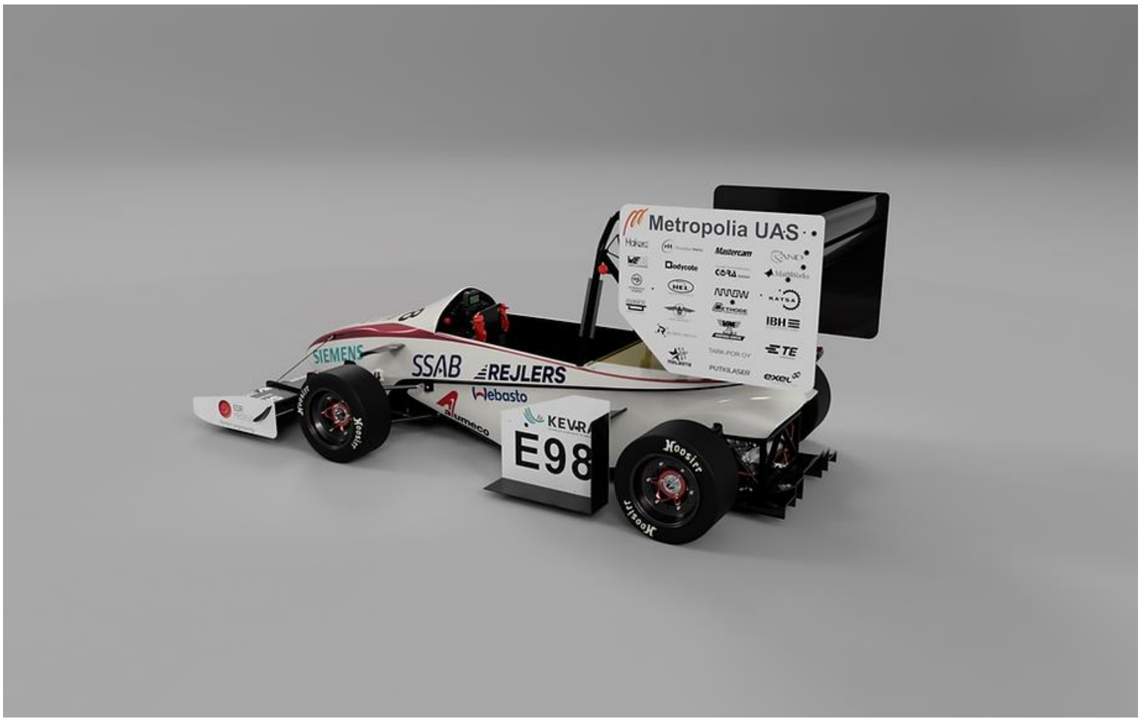

Figure 1. Metropolia Motorsport 2019 car HPF019, rendered. [1.]

Metropolia Motorsport has requested development of a new steering wheel design integrating a display, buttons and potentiometers for on-the-fly vehicle control and adjustments. This is in response to an increase in complexity of their vehicle development process, having developed Four Wheel Drive (4WD), torque vectoring and updated major electrical support systems. This thesis will cover the electronics hardware and software development done for the new steering wheel.

The electronics work of this thesis project is based on earlier prototype development carried out as part of a Metropolia Innovation Project done in

2021. The prototype had an Organic Light Emitting Diode (OLED) display, wireless communications and was battery powered [2], all features that will continue to be developed for this revision.

The design will focus on wireless operations with Bluetooth Low Energy (BLE) 5.0 as the main goal for several reasons. Firstly, having the steering wheel electronics wired in the most optimal way would include major rework on the mechanical side, mainly the steering rack would have to be remade and a different quick release mechanism for the steering wheel would have to be designed. It would also include reworking the wiring harness, all of which would take away development time for other work.

Wireless BLE is also a fairly new technology, and an implementation for this in a formula type steering wheel is a unique and labor effective engineering challenge, which would be for the teams benefit in Formula Student competitions held in Europe, where engineering effort is awarded in the engineering design event with points [3].

2 Project Requirements and Considerations

The project has requirements and limitations set by the Formula Student team itself, as well as limitations regarding time, and capabilities.

2.1 General Limitations

The design and layout of the circuit board is constricted to that of the shape and size of the steering wheel itself. Care must be taken to make sure that not only the shape of the circuit board matches that of what is available in the steering wheel, but considerations also must be made for the height of components. Figure 2 shows a mechanical drawing of the bottom plate of the steering wheel.

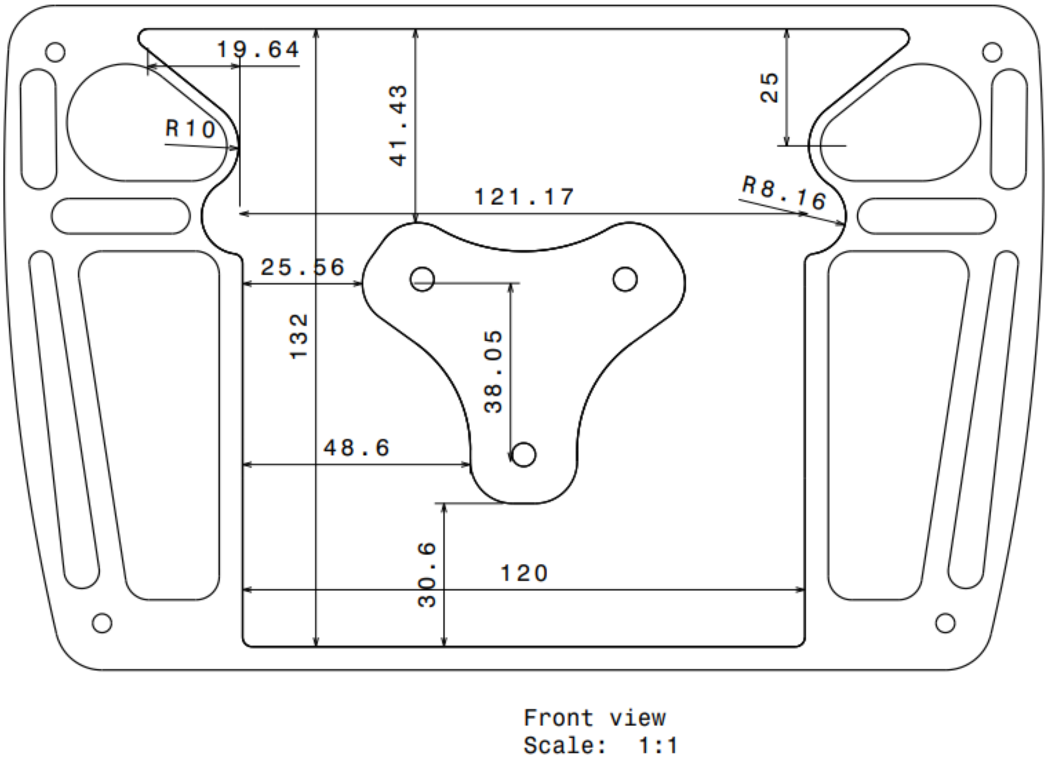

Figure 2. Mechanical drawing of the steering wheel bottom plate.

While there was an open dialogue with the mechanical engineer responsible for the steering wheel design for optimizing the design for Printed Circuit Board (PCB) mounting, the structural rigidity and ergonomics of the steering wheel itself is higher priority than PCB accommodation. PCB rigidity is also important; the components and mounting of the PCB must be able to withstand expected loads brought on for driving, driver egress and a potential crash.

2.2 Metropolia Motorsport

Metropolia Motorsport requested the circuit board to be able to control four push buttons, two rotary potentiometers, one joystick and an OLED display, all of which are mounted on the steering wheel and will be used for Electronic Control

Unit (ECU) communications. This is intended to give great flexibility for the driver of the vehicle to tune and optimize vehicle settings and get detailed warnings and errors from the vehicle to the driver via the OLED display.

The design must support being retrofitted from a wireless design into a wired one without major reworking needed. This is due to uncertainty about the interpretations of rules for the Formula Student competitions, and accounting for the possibility that the radiated Electromagnetic Interference (EMI) from the vehicle while running will be so high that the wireless data transmission will be unreliable.

The steering wheel in battery powered mode was also requested to be able to do at least 12 hours of active runtime before needing to be charged, and the battery should preferably be able to be recharged without taking the battery cell out. The team believes that this comfortably covers the max runtime of any test day with the vehicle on the tracks.

2.3 Time and Capabilities

The timeframe of this project was from December of 2021 to May of 2022, making it a roughly five-month project. Considering this project builds upon work done previously in the innovation project [2], five months was seen as a good amount of time to go from plan to product. However, it must be considered that a five-month time limit limits the amount of prototype circuit boards that can be developed and features incorporated.

The capabilities in production and design are also limited. The manufacturing and testing capabilities are limited by the Metropolia Motorsport and Metropolia electronics lab, which affects the types and sizes of components used. This also limits testing to what equipment is available at the locations mentioned above.

3 Printed Circuit Board Design Process

To ensure a fully working prototype the design process accounted for making two layout designs: one development unit for validating the initial design and the second one as the final layout going inside the steering wheel. This two-design process was also chosen as the mechanical design of the steering wheel was yet to be determined by the time the first schematic was made, and letting development come to a halt until the mechanical design was nearing completion was deemed time ineffective.

The first design called Steering Wheel 2.0 was made with three debug Light Emitting Diodes (LED)'s, a big surface area and integrated potentiometers and buttons to make it easier to start software development. It was also a starting point to find and fix design mistakes that were accounted for on the second board, the schematic of the Steering Wheel 2.0 design is attached in Appendix 1.

The second design called Steering Wheel 2.1, in comparison to the first, is a more compact design made for wiring up external potentiometers and buttons, as well as having only one debug LED. The schematic of this is attached in Appendix 2.

4 Component Selection

The core component choice was affected by the global component shortage currently in effect during the time of writing, which means many ideal components have not been in stock. However, the shortage did not alter the direction of the project objective or its core specifications.

The components were also chosen for hand-solderability. Passive linear components are not smaller than the standard 0603 dimensions, and chip packages such as Ball Grid Array (BGA) and Quad Flat No-Lead (QFN) had been avoided. This is due to cost saving and for repairability in case of a bug in the design. All components listed were used on both designs unless specifically stated otherwise.

All components were checked to comply with the Restriction of Hazardous Substances Directive (RoHS) and Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).

4.1 Microcontroller and Transceiver (Raytac MDBT42Q-512KV2)

The MDBT42Q-512KV2 is a NRF52832 System on a Chip (SoC) module with an onboard ceramic antenna and 32Mhz crystal. It is radio certified in the EU, making it less of a legal and reliability risk to design with compared to implementing the SoC directly onboard the PCB with a self-made antenna solution. The Nordic Semiconductor NRF52832 SoC is one of the most popular BLE SoC’s in the industry, used in products such as the Apple Airtag [5]. It is also in the same family of SoC’s used in the 1.0 revision of the Steering Wheel circuit, making it a known SoC for hardware and software development. It also has all the required digital and analog pins for our application. [4.]

4.2 Display (Newhaven NHD-0420CW-AY3)

The display is an OLED display that can show 20x4 characters on screen at any given time. It is already used in HPF021 as the main information display and is requested to be a part of this revision too. It offers three options for communications: Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C) and parallel. This design will use I2C due to only needing two signal pins for communications. [6.]

4.3 Display Connector (Würth 68612014422)

This display connector was picked as it is supported to be retrofitted on the OLED display. The OLED display also supports being retrofitted with a 10x2.54mm Molex pin header, however the Flat Flex Cable (FFC) connector option was chosen for flexibility reasons as well, as it provides a significantly smaller footprint than with the pin header option. The OLED screen and the steering wheel PCB will use the same connector. The exact recommended part by Newhaven could not be sourced (Molex 52271-2079), however the Würth option chosen is measured to be footprint compatible. [7.]

4.4 Battery (Lithium Polymer)

Lithium Polymer batteries are especially lightweight lithium batteries with a high energy density per kg [8]. This is ideal for motorsport applications where managing weight is critical. The battery is rechargeable, and since its Lithium based there are a lot of options for charging controllers. Two batteries have been used for each of the board designs, for the Steering Wheel 2.0 design, a Philips 18650 mounted on a Keystone 1042 battery holder was used, and the Steering Wheel 2.1 design used a flat cell Cellevia Batteries LP843284 battery with integrated under voltage protection [9].

4.5 Charging Controller (Maxim MAX1811ESA+)

The MAX1811ESA+ is a single cell charging IC made for supporting charging directly from a Universal Serial Bus (USB) ports VBUS and GND pins. It also includes built in safety features such as voltage, current and temperature monitoring, soft starting for near-dead cells and fault condition checking before charging. The IC requires a minimal amount of supporting components, making it suitable for compact designs. [10.]

4.6 Voltage Regulator (Texas Instruments LM3671MFX-2.8/NOPB)

The LM3671MFX is a SOT-23-5 switching DC-DC regulator providing a stable 2.8V output from a 2.7 to 5.5V input, ideal for single cell and USB powered inputs. The IC has a high switching frequency of 2MHz, which means it can be coupled with small passive supporting components and advertises itself as a regulator only needing 3 external components: two ceramic capacitors and one inductor. The switching frequency is so high that extra care must be taken on the layout to ensure it does not interfere with the BLE module’s radio. [11.]

During normal operation the regulator will provide an efficiency between roughly 85% to 95% as checked in the datasheet’s efficiency graph compared to the theoretical calculated consumption mentioned in chapter 5.5.

4.7 Charging Receptacle (GCT USB4085 Receptacle)

The USB4085 is a USB 2.0 compatible USB type C receptacle. It is used for charging the battery cell of the steering wheel, and comes in an exclusively through hole package, making it easily hand solderable and extra durable compared to an SMD part. Being a USB type C receptacle means the steering wheel will not require any special charging cable or charger, as any USB type C charging cable and charger will be supported by the steering wheel. [12.]

4.8 Other parts

4.8.1 Debug Header (Samtec FTSH-105-01-L-DV-007-K)

The debug header was chosen as it is both the same used in the main development kit used in the project, the nRF52-DK, and it supports the standard ribbon cable included in the Segger J-Link EDU Mini, which is the debugger and programmer used for development of the PCB. The header has a 1.27mm pitch between its 9 pins, with one of the pins, pin 7, keyed.

4.8.2 Crystal Oscillator (Citizen CM315D32768DZCT)

While the nRF52832 has its own internal real-time clock, it is good practice and recommended to supply an external crystal oscillator and use it instead of the internal clock, and this will give much greater accuracy from ±250 Parts Per Million (PPM) to ±20PPM [8] in parts of the code using timers. The BLE module has its own 32Mhz crystal built into itself, so that will not have to be provided separately. [14.]

4.8.3 Transistor (Infenion BSS214NWH6327XTSA1)

This transistor was chosen as part of a measurement circuit employed only in the Steering Wheel 2.1 design, where the measurement needs to be turned on, or enabled, before measuring. It was chosen because of its relatively low drain to source resistance at 160mOhms @ 2.8Vgs, and a sufficient gate threshold voltage to work with our logic levels. [13.]

5 Design Theory and Calculations

This chapter is not an exhaustive list of considerations and theory used for design development. Much of the design is based off recommended configurations from main component datasheets as well as common practices, such as having 100nF capacitors close to power inputs for stray noise mitigation. This list is to explain some of the design choices which are not specified in any specific datasheet and can seem confusing by engineering student readers.

While many of these design theories apply to both circuit boards, the reader of this chapter should consider that these theories apply mainly to the Steering Wheel 2.1 board design as it is the final revision.

5.1 Pull-up and Pull-down Resistors

Pull resistors are used several places in both designs for fundamentally important reasons. The pushbuttons and joystick signals are pulled up to VCC to give them a known default state of logical HIGH, and they are required for the SoC to sense the pushbutton transitions.

Other control signals are also pulled high or low for the display, battery charging Integrated Circuit (IC) and SoC reset signal. This is to ensure that these signals are at a known state during power-on, as floating signal pins can in the worst case be unreliable and be triggered high or low by outside factors such as by noise and glitches. Figure 3 shows pull-down resistors being used for the battery charging IC in the battery power schematic to give them a known negative state by default.

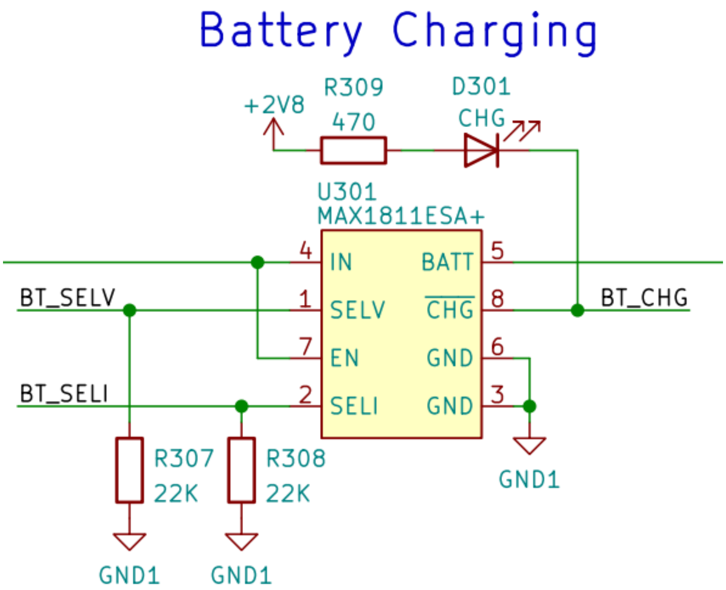

Figure 3. Battery Charging IC drawing in the battery power schematic.

One important issue to consider when choosing pull-up or pull-down resistors for signals the SoC controls, is that the SoC must be able to override these default values. If an SoC's internal pull-up resistor is weaker than the external pull-up resistor, then its functionality is impaired and can end in a signal that is not controllable. The nRF52832 datasheet [17] states the minimum, normal and maximum pull-up and pull-down resistance at 11KΩ, 13KΩ and 16KΩ respectively. The resistor value chosen for the generic pull-up and pull-down was chosen to be 22KΩ as it is an E12 resistor value and is much weaker than the maximum possible internal pull-up and pull-down resistor of the SoC.

The USB standard [15] specifies that signal pins CC1 & CC2 on a USB receptacle or header must include a pull-down resistor of 5.1KΩ 1% for each of the CC pins to indicate that the unit is a device and not host, as well as specifying current handling capabilities. Having pull-up resistors, different resistor values than 5.1KΩ or leaving the pins floating may make the host react abnormally to the connection of the device.

Exceptions of the 22KΩ rule were made for the TWI/I2C line pull-up resistors which are 5.1KΩ. This is due to the I2C standard [16] favoring lower pull-up values for faster high and low transition times, as well as 5.1KΩ was already used by the USB-C CC pins.

5.2 Potentiometer Inputs

The potentiometers used in the designs are designed as simple variable voltage dividers in practice. The washer terminal is the signal output connected to an SoC analog input, while the other two terminals are connected to VCC and GND respectively. The signal output pin will output a voltage value ranging from VCC (2.8V) to GND (0V), which can then be sampled by the SoC's analog to digital converter, or ADC. The connections are shown in Figure 4, with the POT_1 signal going to one of the BLE module's analog input pins.

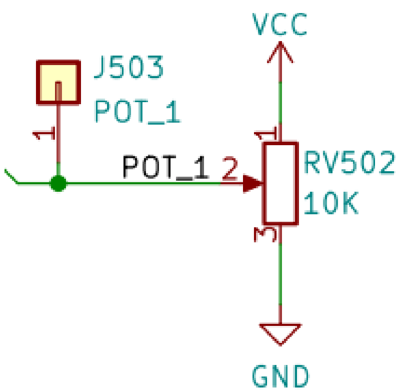

Figure 4. Potentiometer drawing in the user input schematic.

5.3 Battery Measurement Circuit

The battery measurement circuit introduced in the Steering Wheel 2.1 design does two things. Firstly, it has a transistor that is open by default to enable and disable battery measurement to be done. This is to reduce leakage current in case of the circuit being powered but idling at a long period of time. The second part is a voltage divider circuit as the maximum voltage of 4.2V is beyond the maximum rated voltage for the SoC IO pin voltages, which is at VDD + 0.3V, VDD in our case being 2.8V [17].

Three main considerations must be made for the voltage divider: the output voltage, available resistor combinations and resistor values. If the output voltage is too low the ADC pin on the SoC sampling the voltage may struggle to get an accurate reading as the resolution required could be too much for its capabilities and reusing existing resistors in the design is preferred for BOM consolidation reasons. The resistor values should also not be too low as to not leak too much current, but also not so high that the SoC current sink makes the readings skewed.

It was determined that the best option for the design was that the voltage divider would consist of two 22K resistors in parallel for the top part and one 22K resistor for the bottom part. Two parallel 22K resistors functions as one 11K resistor, which results in the output voltage being 2.667V if the input voltage is 4.2V, which is adequate and close to the VCC value of 2.8V.

Another thing to consider for the design in the software part is how long the transistor gate should be open to get a relatively accurate voltage measurement. The transistor and signal trace and wiring will introduce some stray capacitance and resistance, slowing down the rise time of our voltage. An estimation of this can be calculated.

The first step to finding out the rise time of the signal to measure is to find the time constant Tau or τ, which can be calculated by multiplying the trace capacitance and resistance. [18.]

The trace capacitance can be calculated by summing the value of the input and output capacitance of the transistor, as well as estimating trace capacitance.

The resistance can also be measured by looking at the transistors Rds(on) value and estimating trace resistance.

$$C_{Trace} + C_{Transistor} = C_{Tot} \quad (1)$$

$$R_{Trace} + R_{Transistor} = R_{Tot}. \quad (2)$$

$$R_{tot} * C_{Tot} = \tau \quad (3)$$

With the time constant calculated it is possible to multiple the Tau value by 4, the result of which will state how many seconds it takes before the voltage is at 98.2% of its nominal value. Lowering the Tau multiplication will give us a lower percentage, for example Tau * 1 would give the result in 63.2% of its nominal value.

With this theory in mind, we can start calculating an estimate. Trace capacitance and resistance is hard to make an accurate estimation of, as these go through wires that may vary in length and material used. Therefore, an estimate of 100mm is defined. Two online calculators were used, resistance calculator from All About Circuits [20] and the capacitance calculator from EMI Software [19]. For trace resistance the trace width to 0.25mm, length to 100mm, thickness to 0.48mm and temperature to 25, which gave a result of 64.2mOhm. And for the capacitance the width was set to 0.25mm, length to 100, height from ground to 0.48mm which gave a result of 9pF. Inserting these values to our formula, as well as transistor resistance and capacitance from the transistor datasheet, our Tau value is calculated to be 15.9*10^-12, and multiplying this by four gives 63.6pS.

While this gives us a decent estimate, the best practice is to measure the rise time to get the most accurate answer.

5.4 Antenna Considerations

The BLE module we are using uses a soldered ceramic antenna, and the datasheet [4] has some recommendations for optimal performance.

Firstly, the datasheet recommends that there are no copper zones on our PCB under the placement of the antenna, since copper areas can attenuate the wireless signal sent by the antenna. The datasheet also recommends placing the antenna at the board edge for optimal performance as is done in the design. [4.]

Secondly, the datasheet [4] recommends that SoC pins P0.22 to P0.30 only be used for low drive low frequency applications, as these pins are close to the Radio Frequency (RF) module of the SoC, and any fast frequency applications greater than 10KHz can affect RF performance. This is accounted for as these pins are exclusively used for power control and measurement, which does not use any high-speed signaling.

And lastly it is important to take the radiation pattern of the antenna into account to make sure that RF transmissions will transmit at the desired directions.

5.5 Power Consumption and Battery Capacity

To determine the battery capacity required, two main variables must be determined: The power consumption of the circuit board and the required lifetime of the circuit board.

The power consumption can be roughly calculated by taking the main power consuming components, find power consumption data about them in their respective datasheets and compile the current consumptions in a table. Special considerations need to be done to voltage regulators however, as their efficiency depends on their load, and affects the power consumption of the circuit board in a nonlinear way.

The main components in our circuit that draws power in normal operations are the BLE module, OLED display and DC-DC supply. The sum of the current consumption can be found in Table 1.

Table 1. Documented consumption of the main IC's used in the design.

Component	Minimum	Nominal	Maximum
BLE module	0,0003mA	0,7mA	58mA
OLED display	2mA	70mA	135mA
DC-DC Efficiency	0.86	0.89	0.94
Sum	2.28mA	77.77mA	204.58mA

The current consumption of the circuit board will vary a lot depending on how it is used, how many characters are on display at any given time and how often data transmissions happen to give a few examples. A safe approach to making a battery specification within the requirements is to assume the maximum power consumption is always the case. With that it is possible calculate the watt-hours required as shown in formula 4.

$$(Volt * Current) * Hours = Watt/Hours \qquad (4)$$

$$(2.8V * 0.204A) * 12H = 6.85\, W/H \qquad (5)$$

The results state that any battery with more than 6.85Wh of capacity will suffice for this application. The battery chosen for this application has a capacity of 10.36Wh, comfortably above the calculated requirement.

6 Printed Circuit Board design

This chapter will briefly explain the two boards developed and their features, as well as the errata of each board.

6.1 First Circuit Board

The first board was made with two power sources: one 18650 battery option and a wired option for 24V DC input. The power source can be switched with a mechanical SPDT switch included on board, which also ensures that both power sources cannot power the board at the same time. For user input the board has eight microswitches soldered onto it as well as two potentiometers. There is also a FFC receptacle on the board to connect the OLED display, and three controllable LEDs for debug use. Figure 5 shows a photograph of the first board partially assembled.

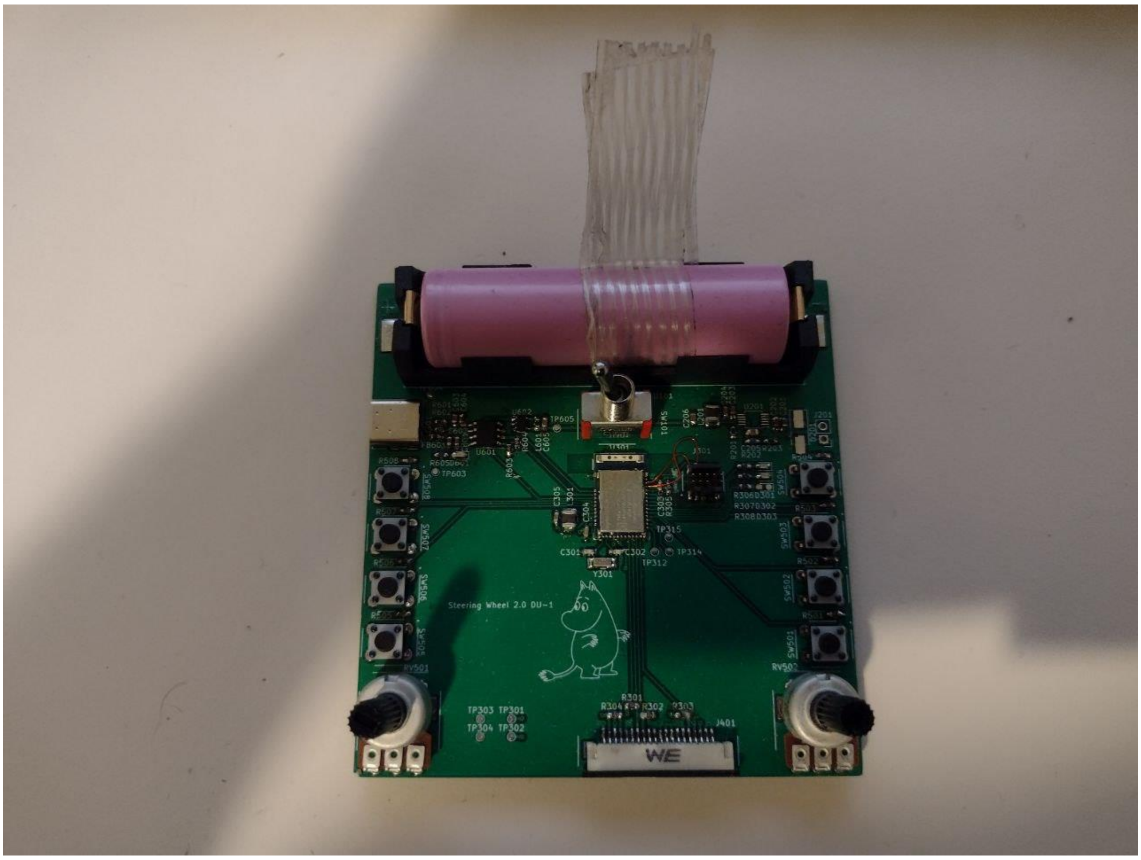

Figure 5. Photograph of the first board design partially assembled.

6.1.1 First Circuit Board Errata

All pushbuttons were incorrectly implemented on the board due to a design error. There was a mistake in the pinout on the schematic versus the footprint, leading all buttons to be nonfunctioning.

The flex cable connector for the OLED display had a discrepancy between the pinout of the OLED display, pinout of the footprint and the pinout of the schematic, leading the pin order to effectively be reversed of what it was supposed to be. This made the OLED display impossible to test out without extensive rework to the circuit board.

POT_0 potentiometer showed much more unstable values and a different range of values when testing out ADC measurements with it compared to POT_1, which turned out to be caused by bad layout routing. The trace connecting the potentiometer washer pin to the ADC of the SoC was routed under the SoC's 32.768KHz crystal oscillator, making the signal very noisy. This error is visualized in Figure 6.

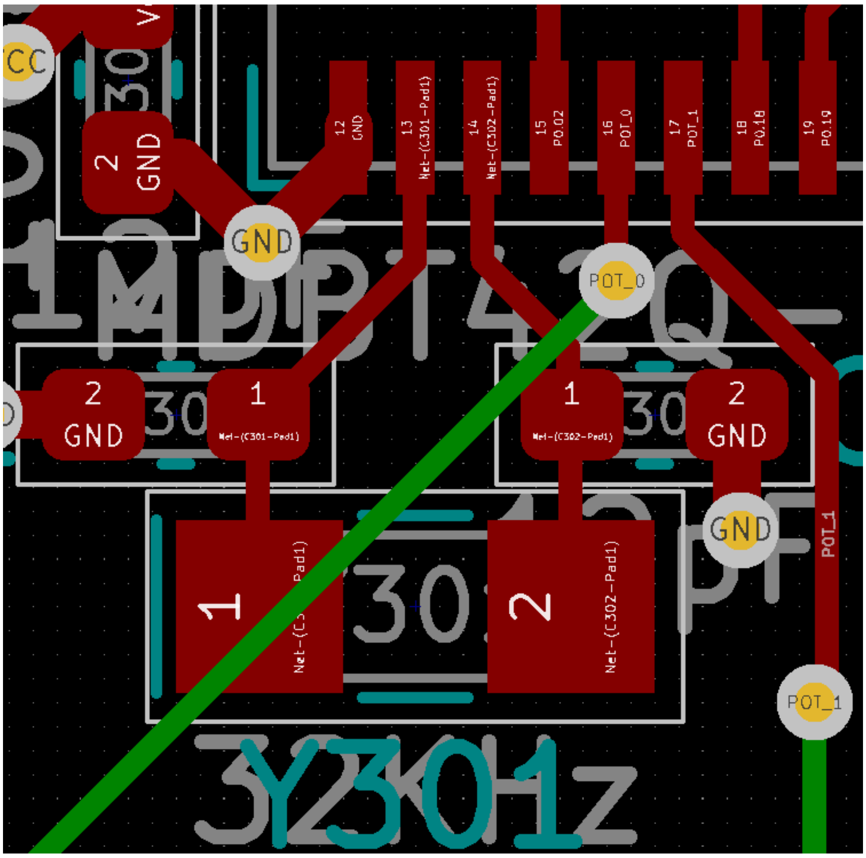

Figure 6. POT_0 trace going underneath the 32.768KHz crystal oscillator.

The debug headers SWDIO and SWCLK pins were mistakenly swapped, requiring rework for the debugging header to become functional.

The pins of the BLE module's footprint proved to be too small for hand soldering with Metropolia Motorsport's soldering equipment; not all pins were soldered properly to the board, which can be seen under a tilted microscope.

The 18650 SMD battery holder used was deemed too brittle; it was hard to hand solder effectively, making it questionable to use in automotive conditions.

The BT_CHG signal monitored by the BLE module outputs a voltage higher than what the modules IO pins are rated for. The signal trace had to be cut to prevent damage to the module, and the second revision must fix this with a voltage divider circuit

6.1.2 Conclusion

This board design proves the value of cross checking and validating designs before heading them into production when taking in to account the mistakes presented in the errata. While the buttons were not critical mistakes due to the nRF52-DK having it for software development, the mistake with the OLED display receptacle rendered it unusable to test the OLED display with. The mistake with the debug connector was fixable with some reworking, however the rework work is brittle and time consuming to do. Overall, the first board served its purpose as a development unit and design validation tool, even though it did not function as intended.

6.2 Second Circuit Board Design

The second board when compared to the first does away with the 24Vinput option, it is ultimately redundant when considering that the team has options for retrofitting this if needed with the use of other circuits in stock, which also decreases the total footprint of the design. The PCB shape itself has changed to be able to fit in the steering wheel, and the circuit itself has been split in two: one PCB for control circuitry and a second PCB for the battery and power regulation. Both are made to be mounted using M4 screws and is be wired together using simple 20AWG wires. This approach was needed to utilize the limited space available inside the steering wheel, with the intent being that the control circuit is mounted at the top while the battery and power regulator circuit is at the bottom end of the steering wheel. The separate circuits are connected on the same PCB, but with breakaway tabs known as mousebites used so that the circuit boards can be cleanly “broken” into two separate PCB’s. Figure 7 shows a photograph of the second design assembled with the OLED display connected.

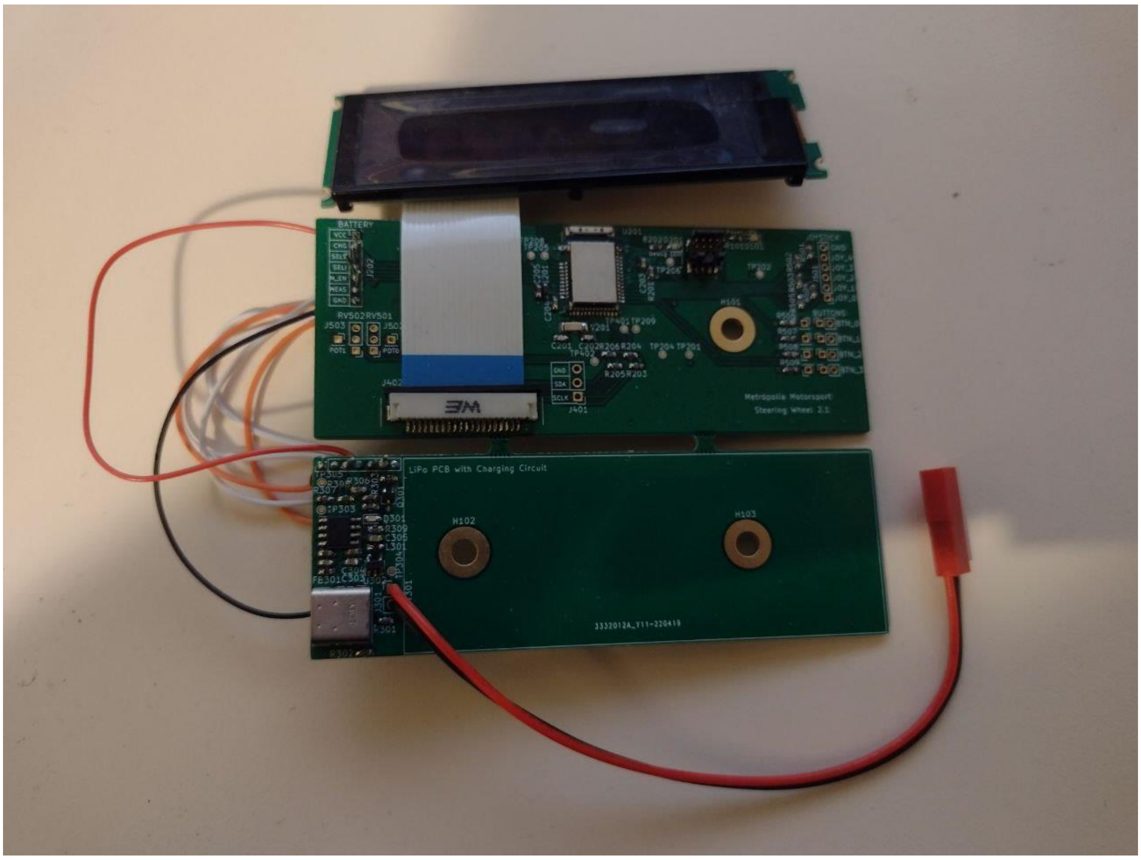

Figure 7. Photograph of the second board design assembled with OLED display connected.

The battery support has been changed from a Samsung 18650 to a flat cell 2800mAh LiPo cell as the 18650 cell was deemed too big to fit the steering wheel design. Besides that, the battery and voltage regulator circuit are functionally the same as the first board design. The control PCB also includes the footprint of a CR2032 battery cell holder, which could be used in a configuration where the steering wheel display is not used.

6.2.1 Second Circuit Board Errata

There is no hardware protection for the LiPo battery until it goes to 3.0V. The battery datasheet [9] states it will cut off power at 3.0V, however this protection should be on the PCB itself too for additional protection and cutting off power earlier will give more headroom for the battery to discharge when left unpowered for longer periods of time. To mitigate this, the SoC software can be programmed to be in a sleep state when battery charge is reported at 0%, and only be woken up by sensing a transition in the BT_CHG sense pin.

The battery measurement circuit did not work as intended, as it was outputting a voltage way different than what was calculated. While the expected voltage output with the battery fully charged at 4.2V was 2.667, the actual output was at 1.850V. The reason for the discrepancy is that the footprint and schematic symbol of the transistor was mismatched, resulting in the drain, gate and source being connected to the wrong pins. This was worked around by removing the transistor and connecting the drain and source in a short, which will give the correct voltage value to the measurement pin of the SoC at the cost of not having the gate control.

The battery measurement circuit location is hard to justify, especially with the CR2032 battery option. It would give more flexibility if the measurement circuit was on the control circuit board, as to make the power management circuit less application specific and more general purpose, with possibilities to reuse it for other designs.

6.2.2 Conclusion

Overall, with some reworking the design is working mostly as expected and is ready to be installed and used on a steering wheel. While there are some issues with the board, they are easily fixable and do not warrant a new prototype.

7 Software Development

Software development for the board has been done initially using the nRF52-DK development kit, then the first board revision, and then the last board revision. Nordic Semiconductor provides two Software Development Kit (SDK)'s; one for the Zephyr real-time operating system and the other, NRF5 for direct programming. The latter environment was picked for familiarity and simplicity's sake from previous development done on the Steering Wheel 1.0 design. However it is noted that NRF5 will not be receiving new BLE feature updates in the future, and development should be switched to be Zephyr based in the future with their NRF Connect SDK [21]. Nordic Semiconductor provides a free license for Segger Embedded Studio, which is the main Integrated Development Environment (IDE) used for software development of this project.

7.1 Bluetooth Low Energy

Bluetooth Low Energy is a wireless technology made for low-power, low throughput radio applications. Despite its name, BLE has no compatibility with normal Bluetooth and is independent of "classic" Bluetooth [22].

Bluetooth Low Energy uses the concept of Profiles, Services and Characteristics visualized in Figure 8, and uses the device role names Peripheral and Central. The Peripheral device is the server which exposes services and characteristics the Central device can read, write and subscribe to notifications from. The Central does not have any services or characteristics the Peripheral can interact with; only the Central controls how data is handled between them [22].

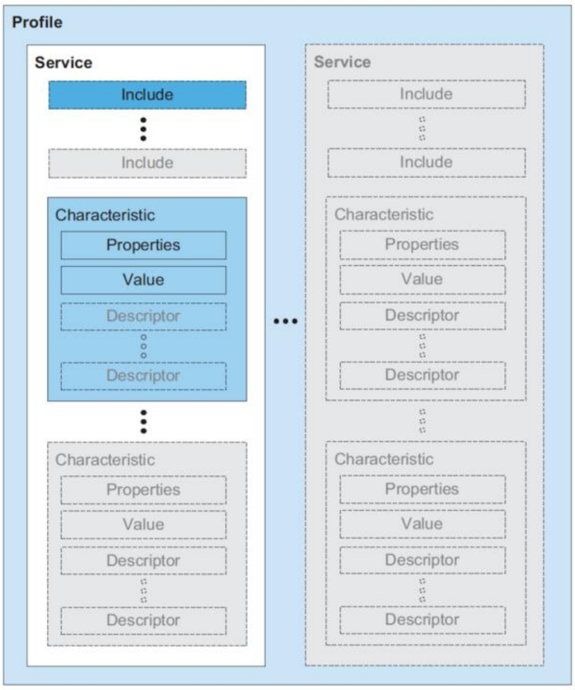

Figure 8. Bluetooth Low Energy Generic Attribute Profile structure. [22.]

The Bluetooth Special Interest Group specifies some standard 16-bit Universal Unique Identifier (UUID)'s reserved for common services used on multiple devices, such as the Battery Level service. These services can be used and accessed as intended by a central device such as a laptop or smartphone without having to install extra software or drivers. The BLE specification does also allow for making your own 128bit UUID's for custom services and characteristics, but these will then require additional software support on the Central to be utilized properly.

The Steering Wheel BLE stack defines four custom services and two Bluetooth Special Interest Group (SIG) defined services: The pushbutton service, the potentiometer service, the joystick service, the display service, the Battery level service and the Generic Access Profile (GAP) service respectively. The GAP service is required by the BLE specification.

The custom services are created as their own libraries, which makes it easy to reuse services for similar BLE applications or future developments of the steering wheel.

7.1.1 Pushbutton Service

The pushbutton service consists of four characteristics. Each characteristic represents a button on the steering wheel and its state, on or off. The characteristics can only be read and is configured so that the central device can subscribe to get notifications from each of the buttons, and each notification is triggered by any state change by any of the buttons.

7.1.2 Joystick Service

The joystick service has one characteristic representing all states the joystick can have; up, down, left, right, idle and middle push. The central device can subscribe to get notifications from the characteristic, and a notification will be sent each time the joystick transitions state.

7.1.3 Potentiometer Service

The potentiometer service has two characteristics each representing the Analog to Digital Converter (ADC) value from POT0 and POT1 of the steering wheel, from 0 to 100%. Each characteristic can be subscribed to from the central device, and a notification will be triggered when the ADC value has changed at least one percentage point.

The ADC measures the voltage from each potentiometer input, as the potentiometers three terminals are connected to VCC, Analog Input and Ground, making it a variable voltage divider. The measurements are triggered every 100ms by one of the built-in timers.

7.1.4 Display Service

The display service has two characteristics named Tx and Rx; The Rx characteristic takes a string sent from the central device formatted as display I2C data and transmits it to the display directly via the I2C bus, whilst the Tx characteristic transmits data sent from the displays I2C line to the BLE module, back to the central device. This effectively makes the display service a wireless I2C bridge, giving the central device a lot of flexibility on what to display on screen.

7.1.5 Battery Level Service

The battery level indicator service relays the remaining battery level of the steering wheel. It shows a value from 0 to 100%, and it can, if configured, notify the central device of a battery level update.

7.1.6 Generic Access Profile Service

GAP is a service required by the BLE specification, that defines important parameters such as device role, advertising and scan response parameters.

7.2 Steering Wheel Software Behavior

At power on, the software will initialize all drivers and services and immediately advertise its presence with the name “Steering_Wheel” so that any central device can find and connect to it. It will advertise indefinitely until it gets a connection.

If a connection is established, it will stop advertising and expose all its services and characteristics to the central device. For best use it is recommended the central device subscribes to the notifications of all the characteristics that support it, as not doing so and polling the steering wheel can make the central device miss out on important driver keypresses. Assuming the central device has subscribed to all notifications, it will be notified of any button presses and their state, joystick directions, potentiometer changes, battery level changes and OLED screen I2C messages. The central device can in turn send I2C messages to the display.

This setup gives great flexibility on the central device’s side as to how to handle user inputs and display information to the user, which for development purposes means that the steering wheel software does not need to be touched for making changes to how the user interface and interactions work.

If the steering wheels wireless communication is disconnected gracefully or abruptly, the steering wheel will start advertising again until it reconnects.

7.3 Demo Software

To be able to test the functionalities and features of the Steering Wheel 2.1 board and validate that they work before installing it on a car, a demo program was developed for the nRF52-DK development board.

The software acts as a BLE central device, and at start-up is immediately looking for the "Steering_Wheel" UUID. Once it finds it, it establishes a connection and subscribes to notifications of all the services of the steering wheel.

While connected, the nRF52-DK board will wait for any notification from the steering wheel. If it gets any button service, potentiometer service or battery service notifications, it will immediately take that data, process it as I2C data for the OLED display, and send that data back to the steering wheel trough the I2C service, which in turn displays the notification data on the steering wheel OLED.

If disconnected, the nRF52-DK will simply start looking for the "Steering_Wheel" UUID again.

8 Testing and validation

Testing and validation are an important part of making sure a design works as intended, and to document its specifications. The measurements done in this part are done for the Steering Wheel 2.1 design, as this is the final design. Some simple tests have been done undocumented, and these tests have uncovered faults noted in the errata of each board.

The measurements done have mainly been limited by time and equipment, as there was neither enough time for precise measurements nor the equipment to do all the desired tests as accurate as possible. It is believed however, that the test done and their accuracy is sufficient for our purposes.

8.1 Functionality Test

To demonstrate the board functionalities and validate it is working, a demo setup was created. It included Steering Wheel 2.1 board and a nRF52-DK development kit running demo software described in chapter 7.3, while steering wheel circuit board would run its production software as described in chapter 7.2. The setup of this is shown in figure 9.

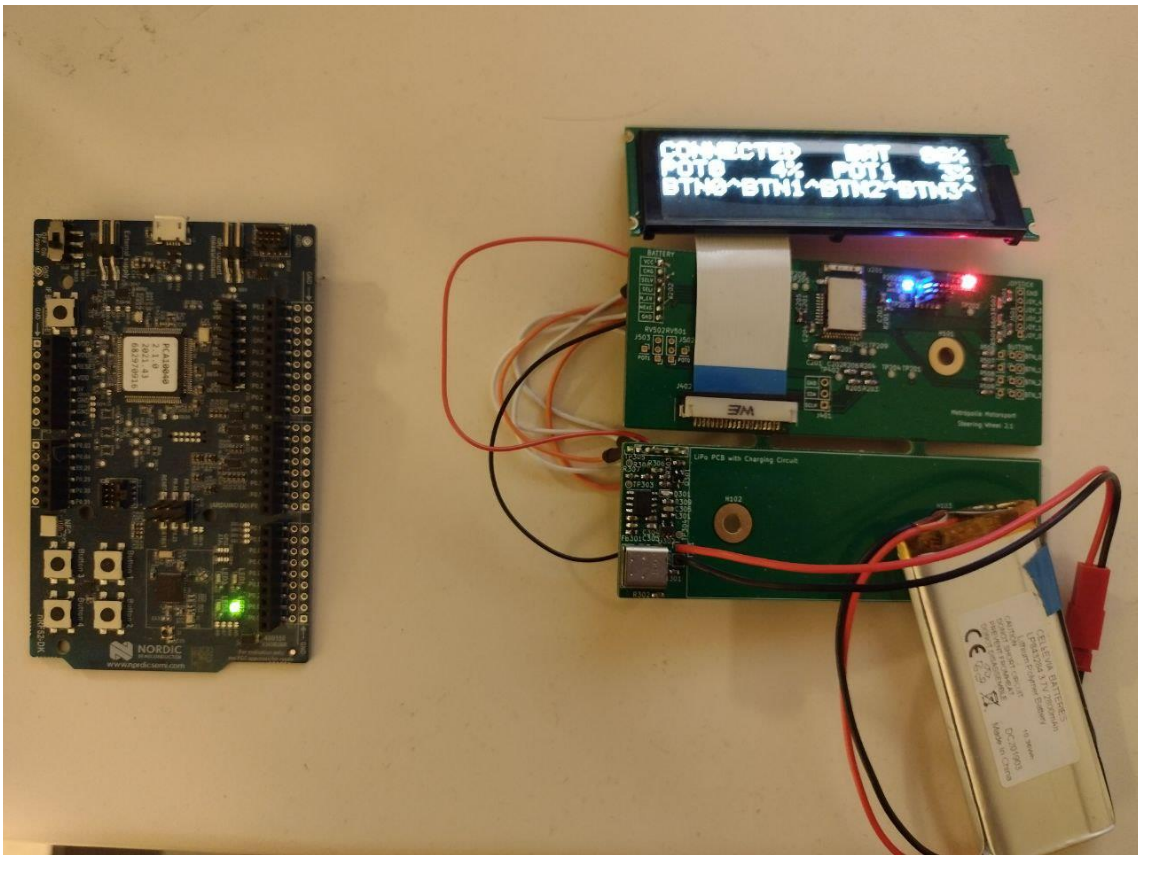

Figure 9. Setup of the functionality test, nRF52-DK on the left and Steering Wheel 2.1 on the right.

Once powered, the nRF52-DK scans the network for BLE advertising packets and specifically looks for the “Steering_Wheel” device name. Once it finds it, it connects to it and subscribes to all services and their notifications. Any notification event happening from the pushbutton, joystick, battery, or potentiometer services will be processed and their data relayed back to the steering wheel display via the I2C service.

The demo software ran as expected, and the demo was successful, showing that all services and functions worked as designed.

8.2 Power Consumption Measurement

Power consumption was measured using a MASTECH MY64 Multimeter in DC current measurement mode with one probe on the +2.8V on the power board and another probe on the VCC of the main circuit. Current was measured in four states: Initial power on, idle, demo running and disconnected. The power consumption was then calculated using the known VCC voltage of 2.8V. Descriptions of the states are as follows.

“Initial power on” has the BLE module advertising, and the OLED screen displaying “SteeringWheelHPF021”

“Idle” has the BLE module advertising, and no characters on the OLED screen.

“Demo running” has the BLE module connected to a nRF52-DK board with the demo software loaded and has all the demo values displayed on the OLED.

“Disconnected” has the BLE module advertising, and the OLED screen displaying “DISCONNECTED”

The results are shown on Table 2.

Table 2. Current & power consumption of Steering Wheel 2.1 in different states.

State	Current	Power
Initial power on	50mA	0.140W
Idle	8.8mA	0.024W
Demo running	135mA	0.378W
Disconnected	46mA	0.128W

It is believed that some optimizations can make the current consumption slightly smaller, which would be especially ideal for the idle state. One such way would be to disconnect the power LED used in the design, as the current consumption from that is calculated to be 6mA. Another way would be to pull the OLED RESET pin low by default, to properly have it shut off.

It is worth noting that despite current consumption is lower than the maximum documented consumption calculated in Table 1, it is unrealistic that both the OLED and BLE module would consume maximum current for any prolonged period at the same time and that these measurements are closer to that of a realistic power draw. Overall, this is within expectations, and this test can be deemed a success.

8.3 Voltage Measurement

Key voltage nodes were measured to document and verify that design choices worked as intended. These were VCC, BT_CHG, +BATT, BT_SELI and BAT_MEAS.
While it would be possible to measure all voltage nodes, it was deemed unnecessary as many of them work or are designed the with the same pull-up or pull-down resistor combinations or was deemed irrelevant to measure since they have been designed around different datasheet specifications for core components, and already proved to function as expected.

The voltage nodes were measured with the board powered on and running production software. BT_CHG was measured with both the charging indicator on and off, and the BAT_MEAS node was measured with the battery fully charged. Table 3 shows the result of the measurements.

Table 3. Measured Steering Wheel 2.1 voltages.

Node	Voltage
VCC	2.810V
BT_CHG (LED ON)	44mV
BT_CHG (LED OFF)	1.9V
BT_SELI	2.786V
BAT_MEAS	2.795V

These results are within margins of error and as expected. One thing to note is that while the BAT_MEAS voltage fully charged is slightly higher than the calculated value, it is due to the resistors 1% and not a result of any design faults.

8.4 Distance Test

Distance measurement was done using the circuit board and nRF52-DK loaded with the demo software. This was tested at the Metropolia Leiritie 1 campus, where the nRF52 board would stay static on in one end of the building, while an operator walked with the circuit board away from the nRF52-DK board, checking if the circuit board started experiencing any significant delay or slowing down, and seeing how far they could go before the board disconnect.

Things to keep in mind is that the measurement area was indoors and had noise on the 2.4GHz frequency band from both Wi-Fi and other Bluetooth and BLE devices, which is the frequency band used on our test. The test conducted was also line-of-sight, with no physical obstructions between the nRF52-DK board and the steering wheel board

Significant slowdown of performance happened at 60m distance, while a full disconnect event happened at 80m distance. This can be considered successful, as it indicates that there are no major design implementation flaws of the BLE module.

8.5 Battery Lifetime Test

To test if the circuit board will last the 12 hours as specified by Metropolia Motorsport, a simple test was done with one nRF52-DK with the demo software loaded and the battery of the steering wheel board fully charged.

All the demo software display characters were displayed on the screen to simulate as much current consumption as realistically possible. Due to noise in the floating ADC pins where a potentiometer is supposed to be wired up, the NRF52-DK development board and steering wheel circuit board would regularly communicate new ADC states and new display character prints as to simulate real, expected communication between the steering wheel board and the ECU.

The test started 2.5.2022 at 00:50 and was concluded at 12:50 the same day, exactly 12 hours. The battery voltage had dropped from the start measured 4.15V to 3.66V during that time, indicating there was some power left and the test could have gone for longer. However, it was determined that due to the lack of battery undervoltage circuitry on the circuit board, it would be unwise to run the test for longer.

9 Conclusions and Improvements

9.1 Improvements

There are a couple of improvements that could be done with the design and design process itself, including what is in the errata.

For retrofitting the design to a completely wired design, the circuit board should have included a differential communication option such as differential I2C. This was planned, but not executed as the transceiver chips required were deemed very difficult, if not impossible to obtain, likely from the global chip shortage experienced at the time of writing.

The nRF52832 module used should have been one with a U.FL or other external antenna connector. The mechanical buildup of the steering wheel is not ideal for having an integrated antenna, and an external one would be preferred for better signal performance. The reason this project did not opt for such a module is due to a shortage of such modules.

The design process should have included preliminary wireless testing to get an early indication of the reliability and feasibility of using a BLE design in the vehicle. This was planned by using two nRF52-DK development boards mounted in the vehicle running BLE throughput test software measuring packet loss and transmission delay. This was not done as the vehicle used, HPF021, was disassembled before the test setup could be completed, and the next opportunity for testing would be in May, well after the design deadline.

9.2 Conclusion

Ultimately the project has been successful and reached its goals. While there was not enough time to test the steering wheel electronics with the new HPF022 vehicle, the capabilities and functionalities are working and has been demonstrated by the software demo developed and presented in chapter 8.1.

It is expected that the design will be used in HPF022 in either its wireless or wired form soon, and due to its flexible software and hardware design it should be easily reusable for future vehicles with little to no changes.

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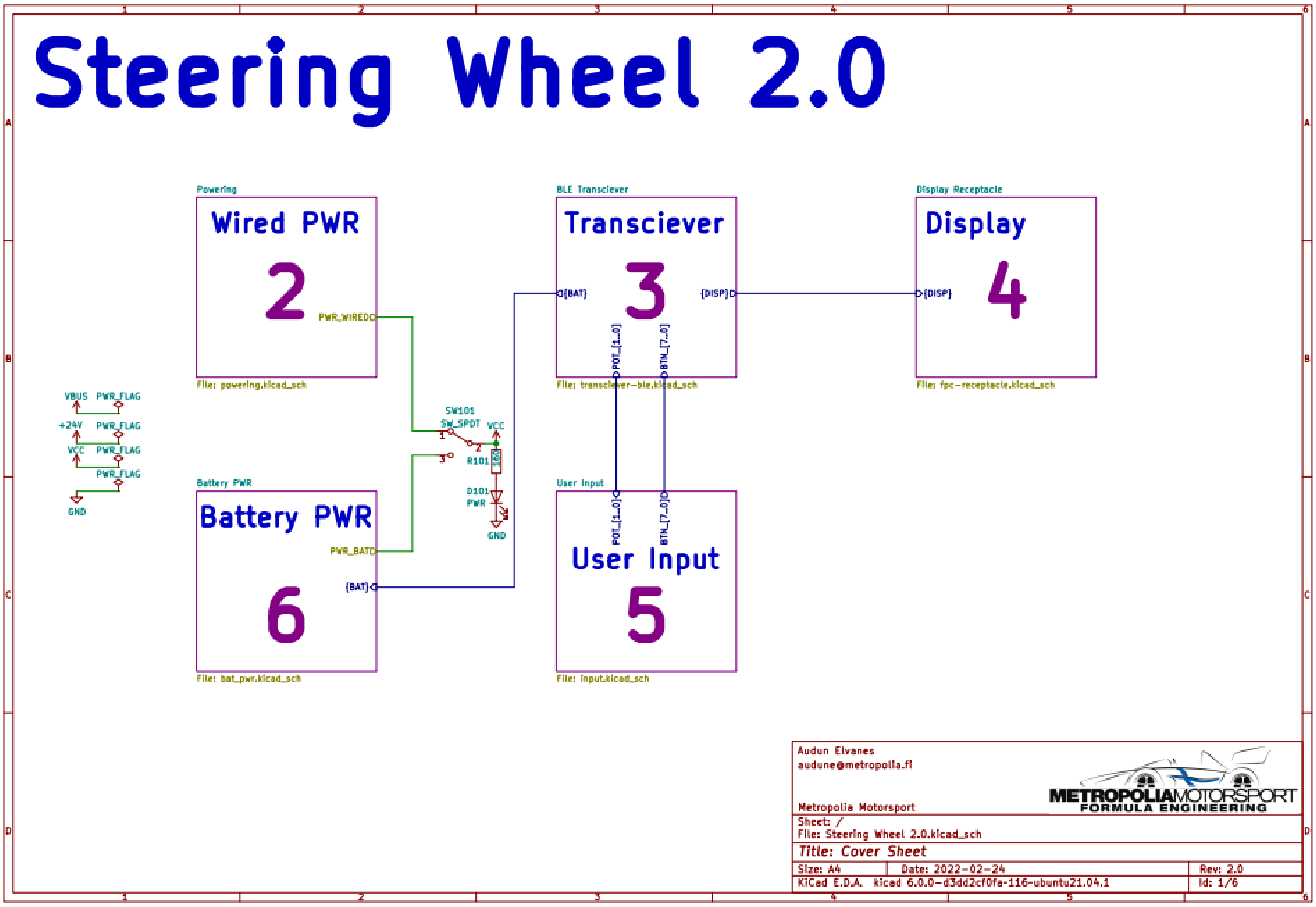
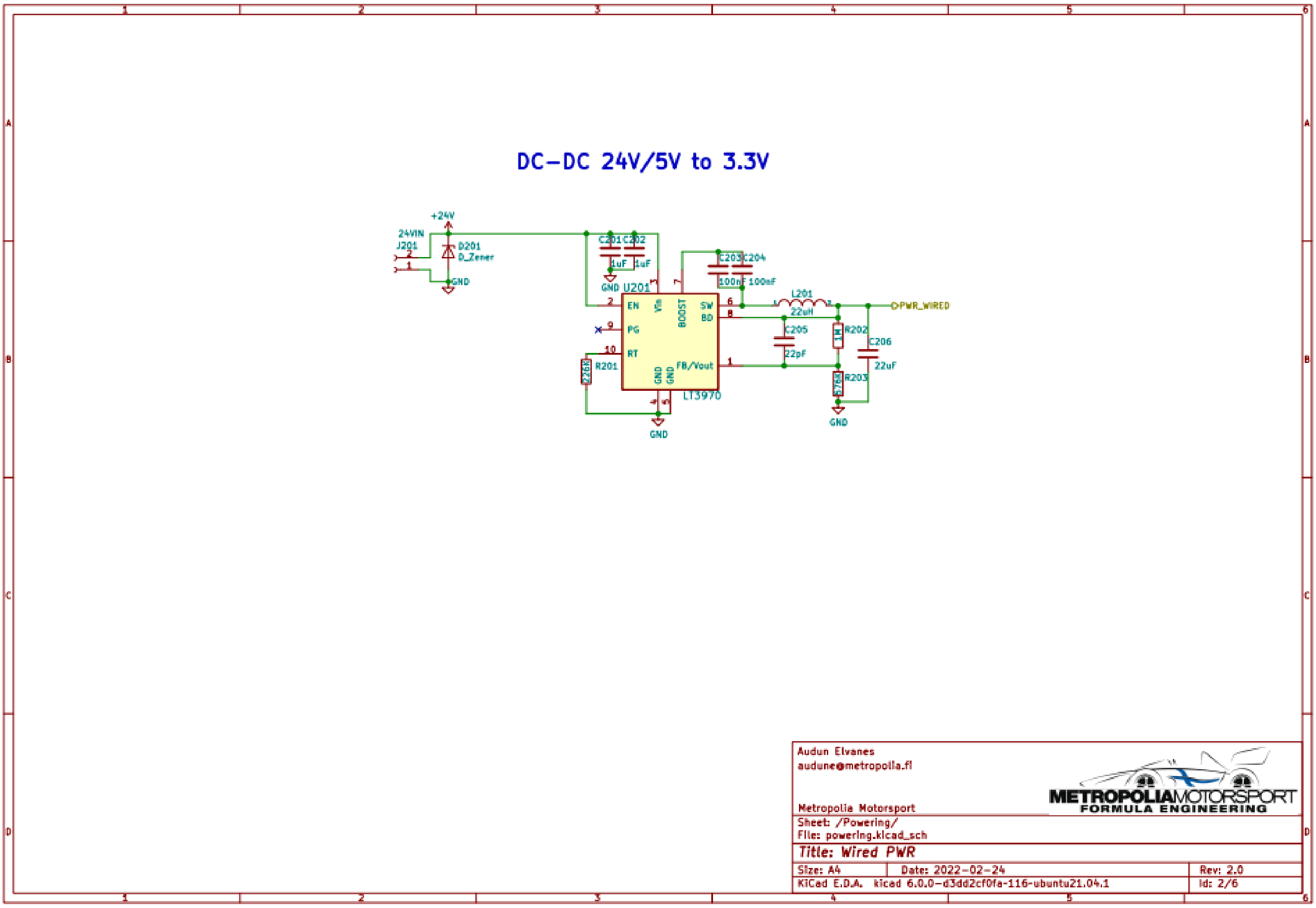
Steering Wheel 2.0 Schematic

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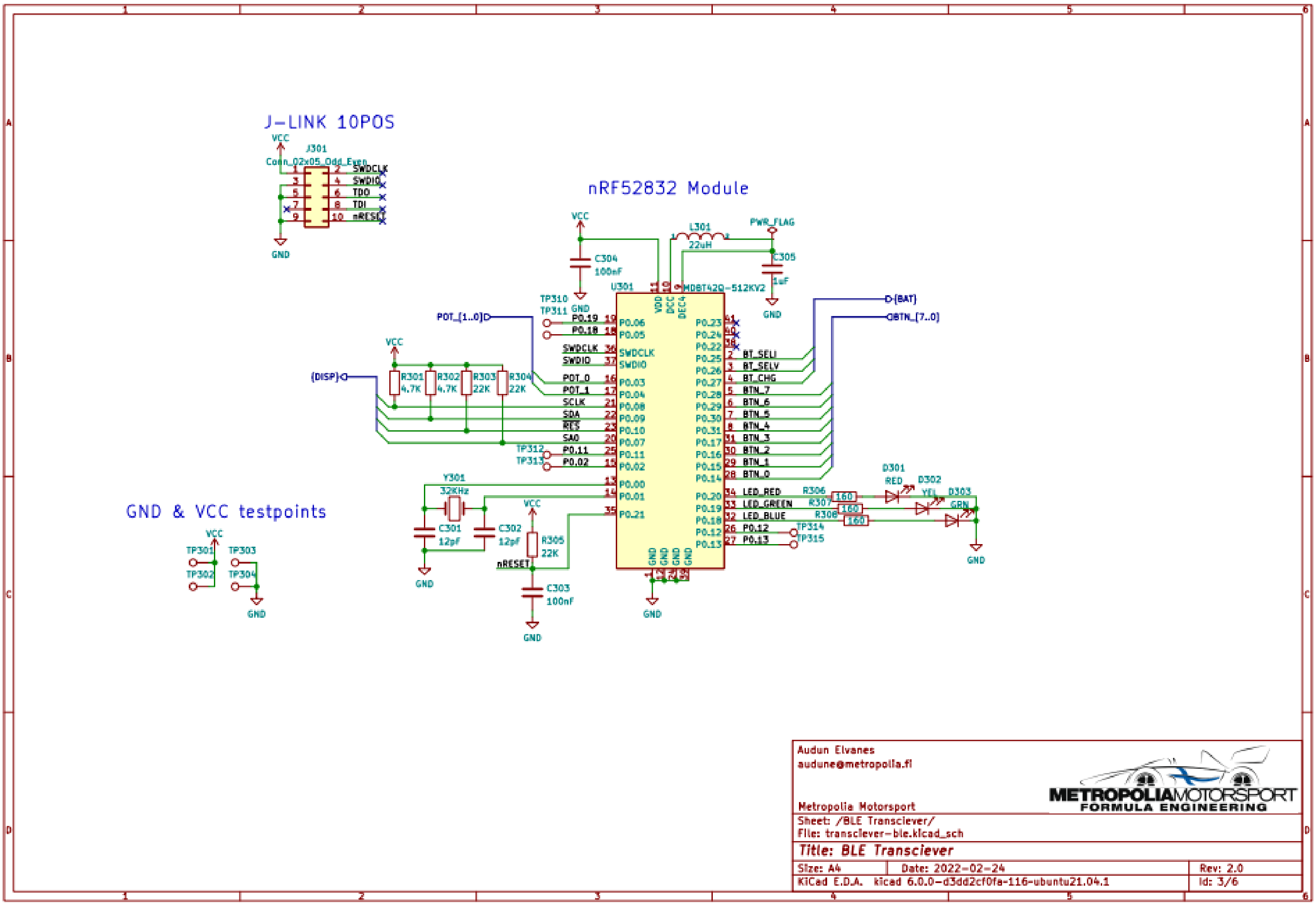
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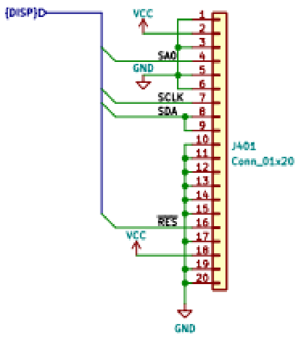

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Metropolia Motorsport

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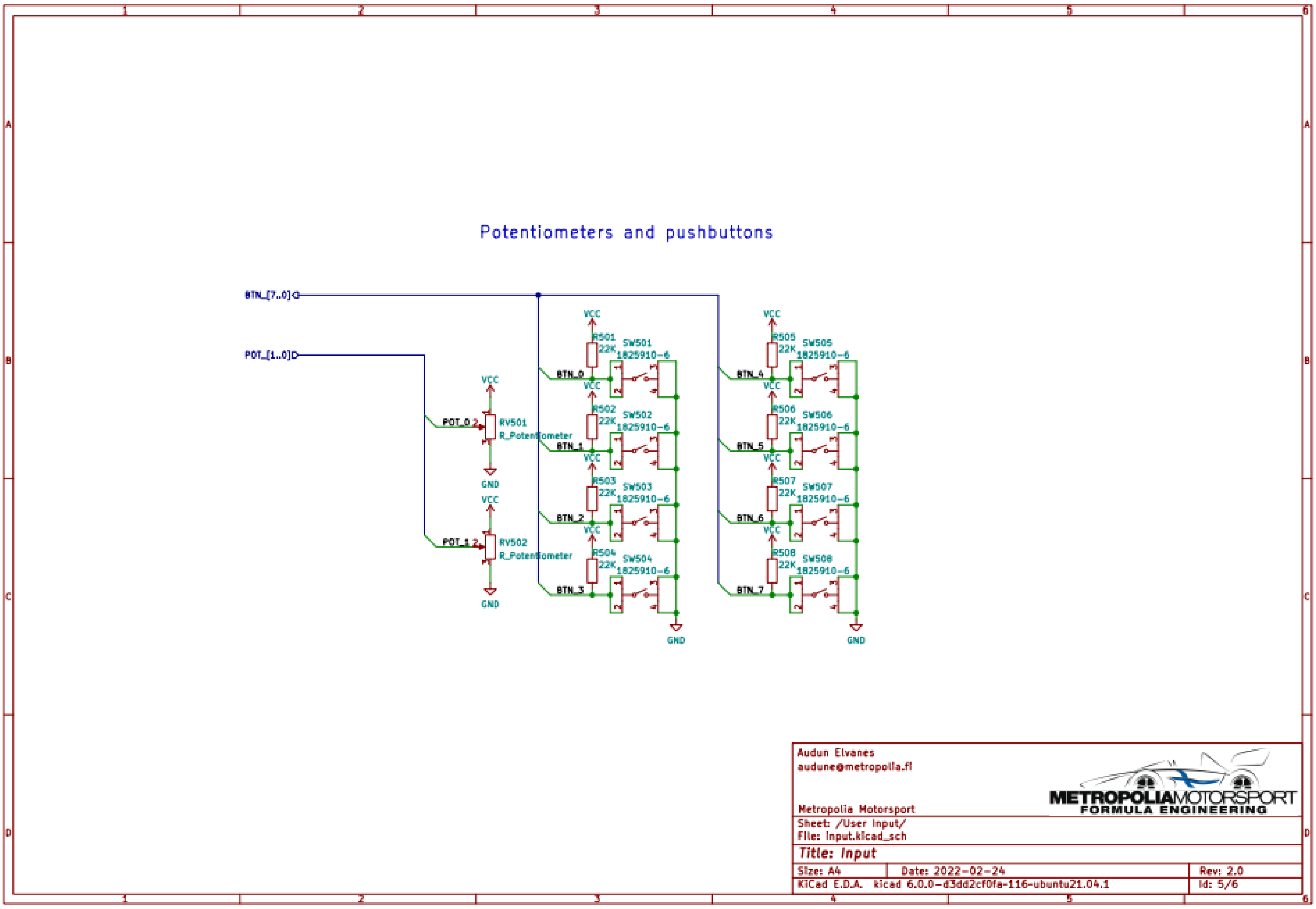
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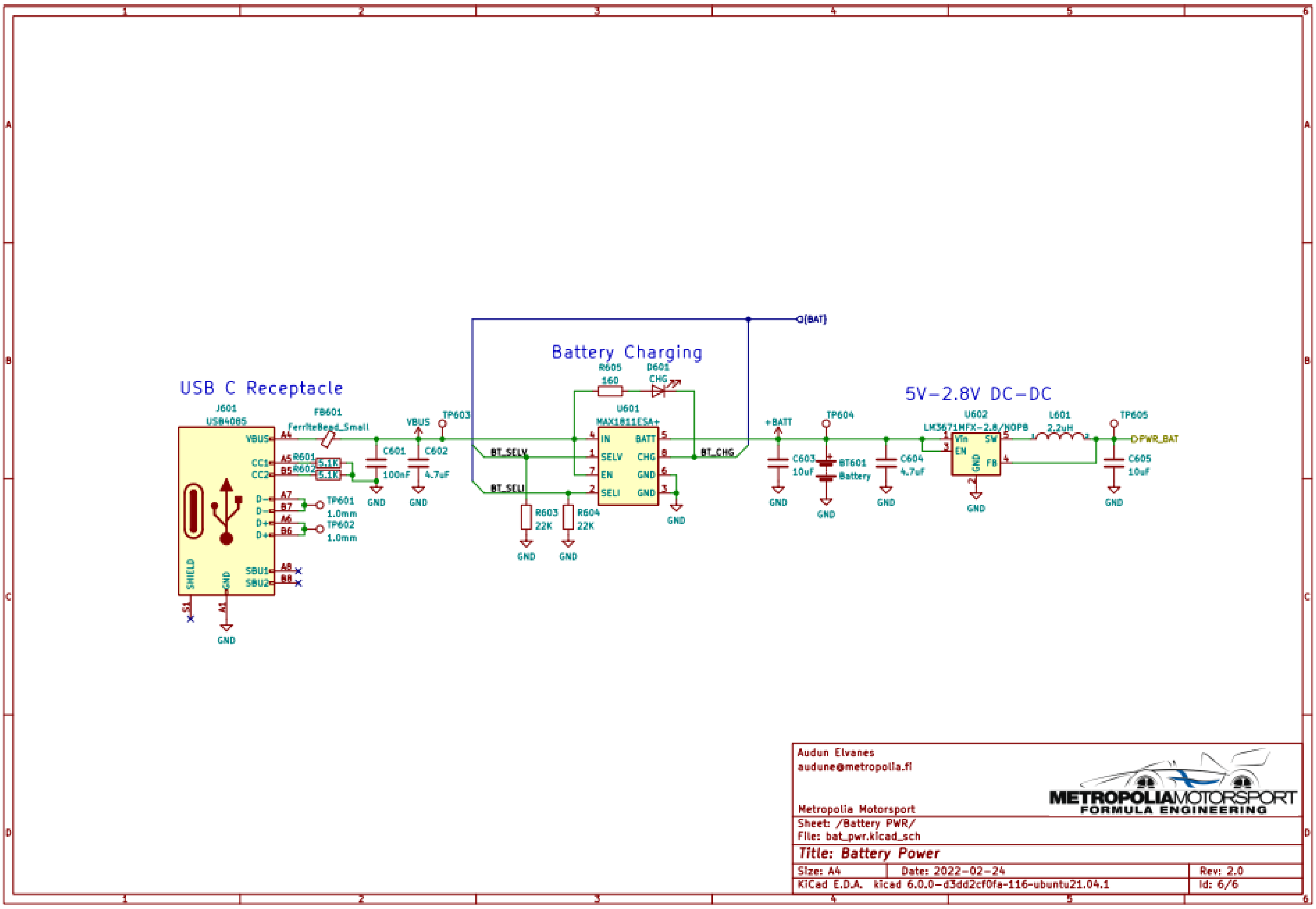
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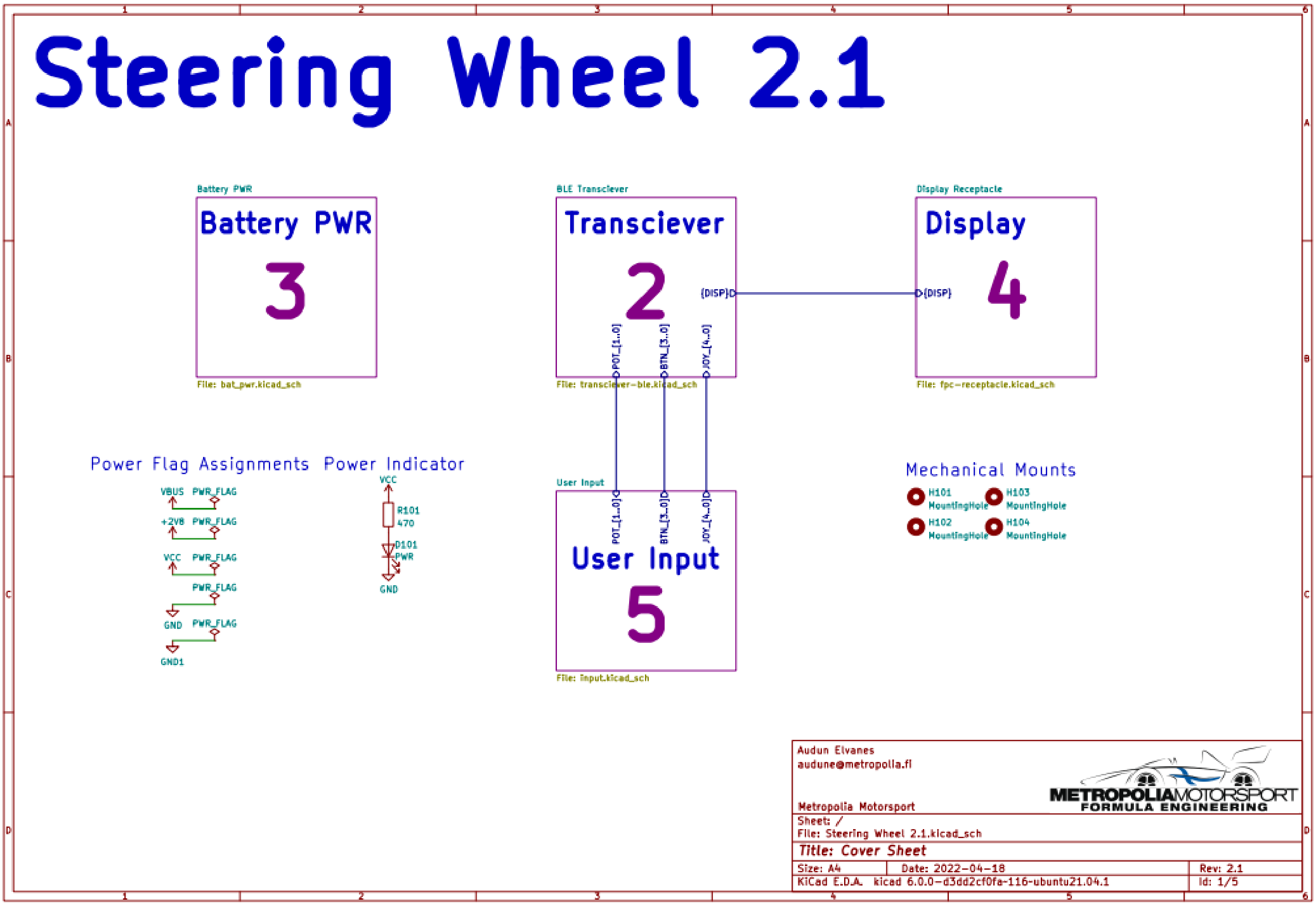
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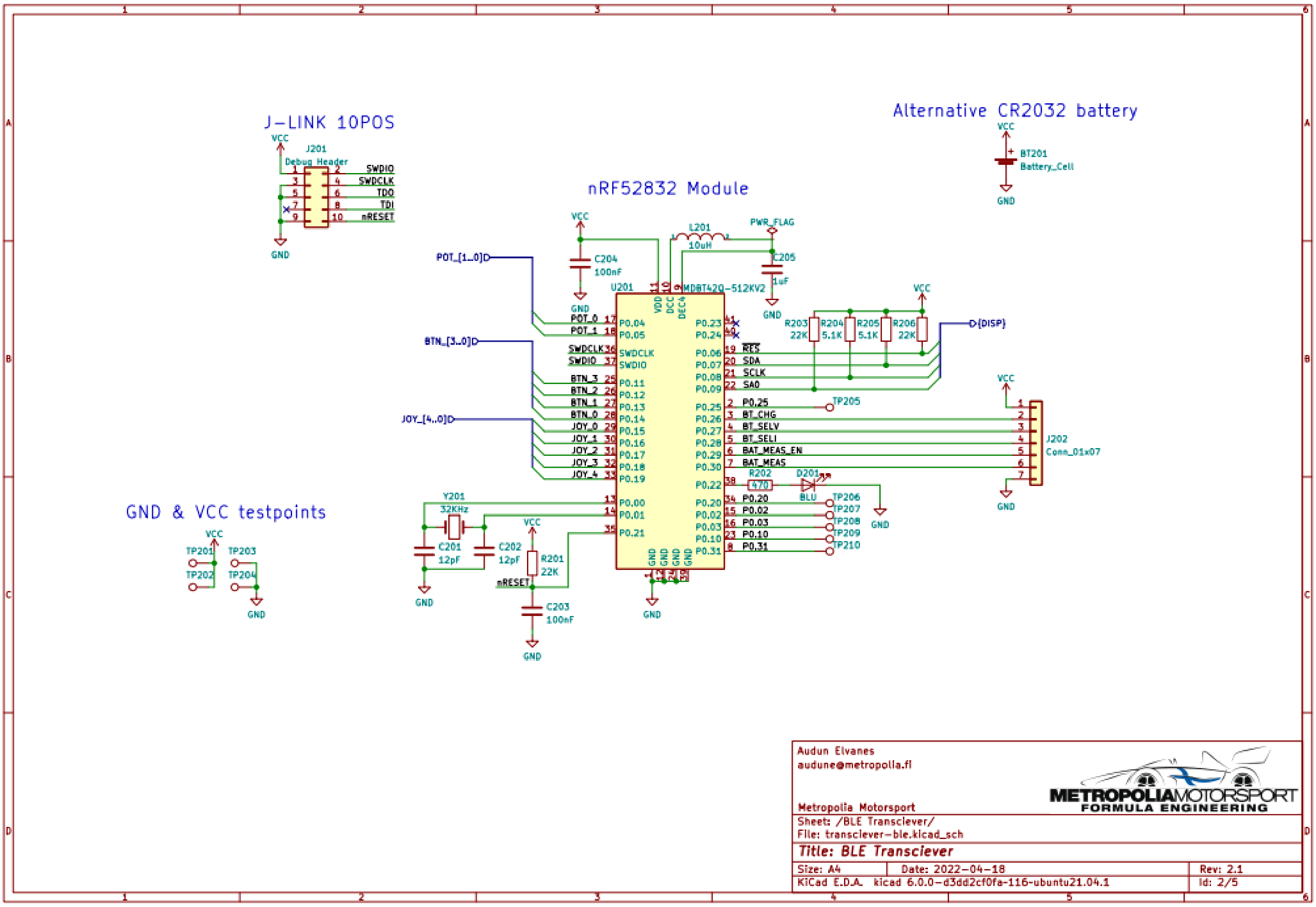
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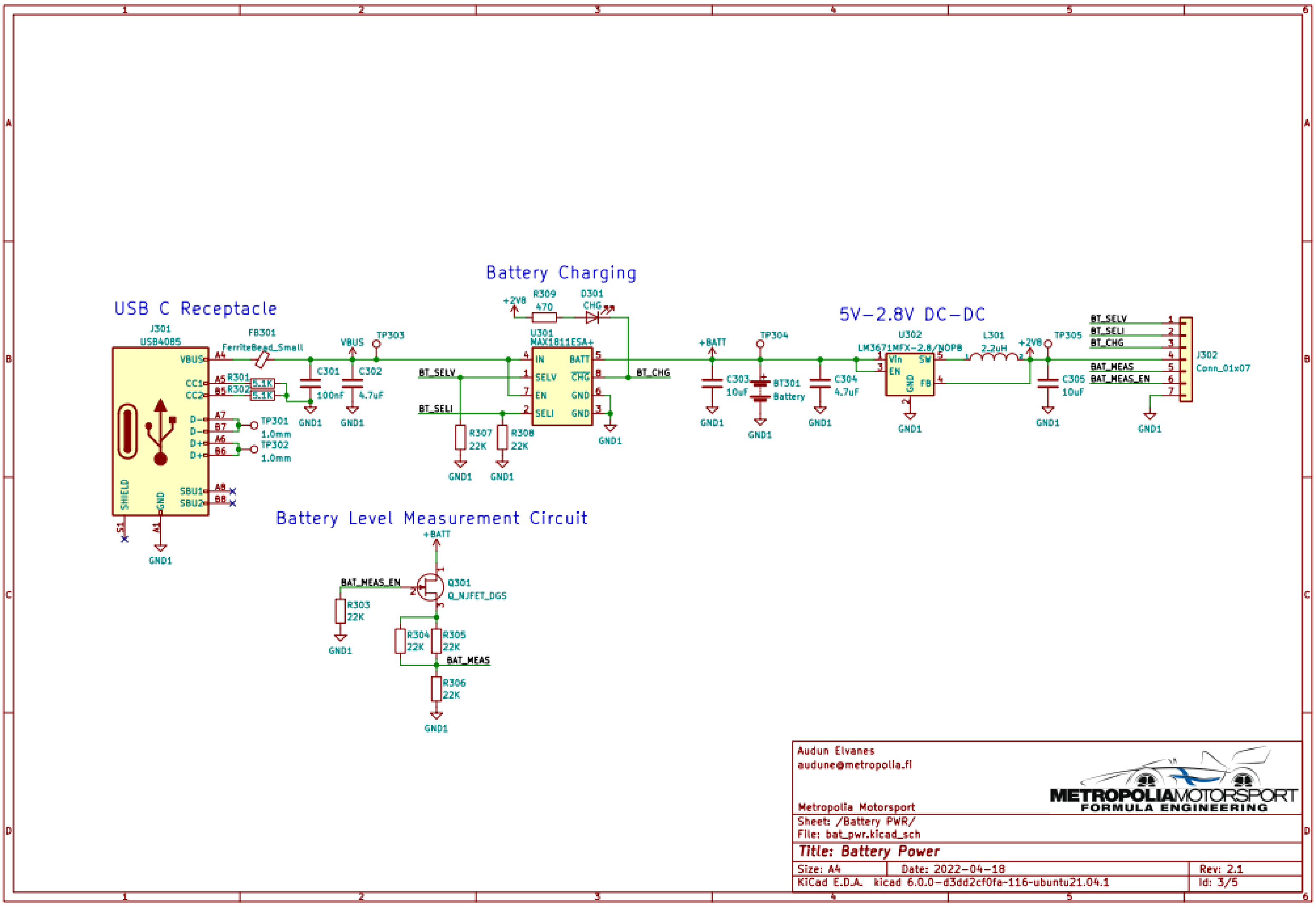
10uH
PWR_FLAG
C205
1uF
R203
22K
R204
5.1K
R205
5.1K
R206
22K
{DISP}
RES
SDA
SCLK
SA0
P0.25
BT_CHG
BT_SELV
BT_SELI
BAT_MEAS_EN
BAT_MEAS
TP205
J202
Conn_01x07
R202
470
D201
BLU
TP206
TP207
TP208
TP209
TP210
Y201
32KHz
C201
12pF
C202
12pF
R201
22K
C203
100nF
Alternative CR2032 battery
BT201
Battery_Cell
GND & VCC testpoints
TP201
TP202
TP203
TP204
VCC
GND
Audun Elvanes
audune@metropolia.fi
Metropolia Motorsport
METROPOLIA MOTORSPORT
FORMULA ENGINEERING
Sheet: /BLE Transciever/
File: transciever-ble.kicad_sch
Title: BLE Transciever
Size: A4
Date: 2022-04-18
Rev: 2.1
KiCad E.D.A. kicad 6.0.0-d3dd2cf0fa-116-ubuntu21.04.1
Id: 2/5


Battery Charging
USB C Receptacle
5V-2.8V DC-DC
Battery Level Measurement Circuit
J301
USB4085
FB301
FerriteBead_Small
VBUS
TP303
R309
470
D301
CHG
U301
MAX1811ESA+
+BATT
TP304
U302
LM3671MFX-2.8/NOPB
L301
2.2uH
+2V8
TP305
BT_SELV
BT_SELI
BT_CHG
BAT_MEAS
BAT_MEAS_EN
J302
Conn_01x07
C301
100nF
C302
4.7uF
R301
5.1K
R302
5.1K
TP301
1.0mm
TP302
1.0mm
R307
22K
R308
22K
C303
10uF
BT301
Battery
C304
4.7uF
C305
10uF
GND1
Q301
Q_NJFET_DGS
R303
22K
R304
22K
R305
22K
R306
22K
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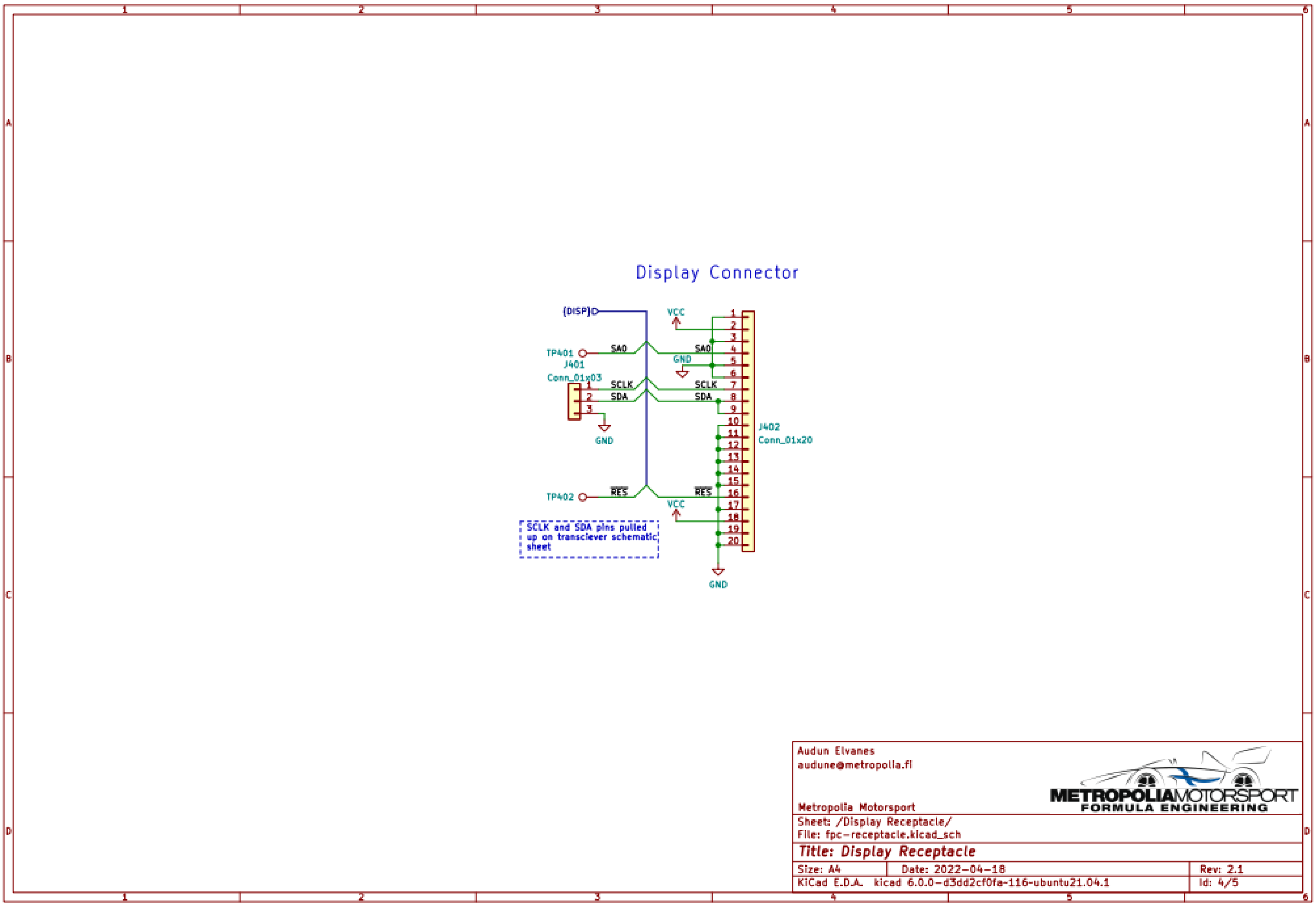
METROPOLIA MOTORSPORT
FORMULA ENGINEERING
Sheet: /Battery PWR/
File: bat_pwr.kicad_sch
Title: Battery Power
Size: A4
Date: 2022-04-18
Rev: 2.1
KiCad E.D.A. kicad 6.0.0-d3dd2cf0fa-116-ubuntu21.04.1
Id: 3/5


Display Connector
[DISP]
TP401
J401
Conn_01x03
SA0
SCLK
SDA
GND
VCC
J402
Conn_01x20
TP402
RES
SCLK and SDA pins pulled up on transciever schematic sheet
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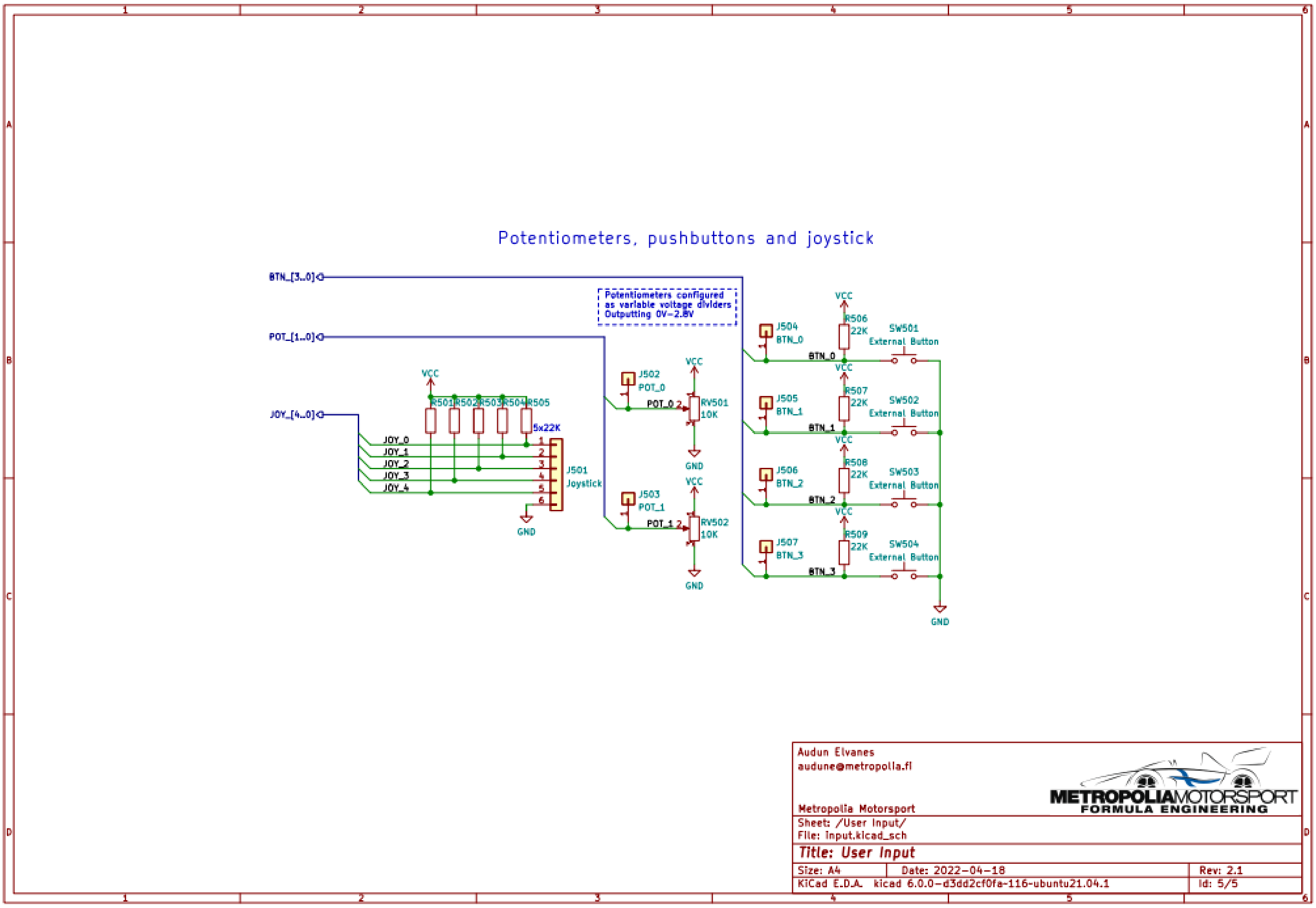
Metropolia Motorsport
METROPOLIAMOTORSPORT
FORMULA ENGINEERING
Sheet: /Display Receptacle/
File: fpc-receptacle.kicad_sch
Title: Display Receptacle
Size: A4
Date: 2022-04-18
Rev: 2.1
KiCad E.D.A. kicad 6.0.0-d3dd2cf0fa-116-ubuntu21.04.1
Id: 4/5


Potentiometers, pushbuttons and joystick
BTN_[3..0]
POT_[1..0]
JOY_[4..0]
Potentiometers configured as variable voltage dividers Outputting 0V-2.8V
VCC
R501 R502 R503 R504 R505
5x22K
JOY_0
JOY_1
JOY_2
JOY_3
JOY_4
J501 Joystick
GND
J502 POT_0
POT_0
RV501 10K
J503 POT_1
POT_1
RV502 10K
J504 BTN_0
R506 22K
SW501 External Button
BTN_0
J505 BTN_1
R507 22K
SW502 External Button
BTN_1
J506 BTN_2
R508 22K
SW503 External Button
BTN_2
J507 BTN_3
R509 22K
SW504 External Button
BTN_3
Audun Elvanes
audune@metropolia.fi
Metropolia Motorsport
METROPOLIA MOTORSPORT FORMULA ENGINEERING
Sheet: /User Input/
File: Input.kicad_sch
Title: User Input
Size: A4
Date: 2022-04-18
Rev: 2.1
KiCad E.D.A. kicad 6.0.0-d3dd2cf0fa-116-ubuntu21.04.1
Id: 5/5