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MULTICHANNEL BATTERY TESTING SYSTEM

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Multichannel battery testing system

This thesis focuses on the hardware and software development of a battery testing system capable of concurrently testing eight single cell Li-ion or Li-Po rechargeable batteries while providing overvoltage, undervoltage and temperature protection. The battery testing system can log test measurements onto an SD card, which provides a computer independent backup.

The battery testing system is computer controllable: the software allows changing various parameters, creating customized test scenarios and shows live plots during tests. When a test ends a conclusive plot will be shown. The system's supported observable battery parameters are voltage, current, temperature and the amount of electric charge/discharge.

Mitme kanaliga akutestimisüsteem

Käesolev bakalaureusetöö kirjeldab akutestimisüsteemi tarkvara ja riistvara arendust. Akutestimissüsteem on võimeline samaaegselt testima kaheksat üheelemendilist Li-ion või Li-Po akut, kaitstes neid alalaetuse, ülelaetuse ja kõrge temperatuuri eest. Seade saab kirjutada SD mälukaardile testi mõõtetulemused, mis tagab arvutist sõltumatu andmete varundamise.

Akutestimissüsteem on arvutijuhitav: tarkvaraga saab seadistada erinevaid testi parameetreid, mis võimaldab luua erinevaid teststsenaariume. Tarkvara kuvab käimasoleva testi ajal graafikuid reaalajas ja testi lõpus kokkuvõtva tulemuste graafiku. Testimisüsteem võimaldab jälgida akude pingeid, voole, temperatuure ja jälgib akude laetuse ning tühjenemise tasemeid.

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Acronyms and abbreviations

ADC	Analog-to-digital converter
DAC	Digital-to-analog converter
DMA	Direct memory access
FIFO	First in, first out
GND	Ground
GPIO	General-purpose input/output
HAL	Hardware abstraction layer
I^2C	Inter-Integrated Circuit
IC	Integrated circuit
Li-ion	Lithium-ion
Li-Po	Lithium-ion polymer
MCU	Microcontroller unit
MOSFET	Metal–oxide–semiconductor field-effect transistor
PCB	Printed circuit board
PSU	Power supply unit
PWM	Pulse width modulation
SCL	Serial Clock Line
SD	Secure Digital
SDA	Serial Data Line
SDIO	Secure Digital Input Output
SPI	Serial Peripheral Interface Bus
UART	Universal asynchronous receiver/transmitter
USB	Universal Serial Bus

1. Introduction

Rechargeable batteries are used in a wide variety of applications. Conducting tests on rechargeable batteries might be necessary to verify battery's suitability in a specific application and when comparing batteries. Testing used batteries can help identify which ones have passed their rated usable lifespan or are close to it [1]. In such a scenario, rather than periodically swapping out batteries, battery testers could be used to more closely evaluate the state of a battery, resulting in environmentally and economically favourable outcomes.

Quantifying all conditions of a battery cannot be done in short, comprehensive tests. The state-of-health of a battery can be estimated to various degrees of accuracy based on available symptoms [1]. In order to ease the testing procedures, battery testing equipment can be used. The sophistication of the battery testing equipment determines which parameters of the battery can be directly or indirectly measured.

Measuring parameters of a battery could be carried out with non-specialized equipment, but it can be more time-consuming and in case of human error or misuse, also damaging for the equipment and for the battery. Battery testing equipment may implement safeguards to avoid damage and provide different types of automated tests in order to analyse different aspects of the battery. The equipment may have different types of interfaces, i.e. on-board dials, screens and other indicators, but it may also be controllable with computer software, which provides the user interface [2].

This thesis gives an overview of the design of a computer controllable multichannel battery testing system. The highlights of the testing system include the ability to test up to eight batteries concurrently, user configurable test parameters and safeguards implemented to protect batteries from various hazards. Areas discussed in the thesis cover the requirements of the system, electronics and software design. During the development process a working prototype of the battery testing system was built. The capabilities of the prototype are examined alongside with data collected from conducted tests.

2. Overview

Battery performance depends on how the battery is used and on the environmental conditions under which it is used. These environmental conditions can be deficiently specified in market advertising [3]. When comparing batteries, environmental conditions and testing parameters must be similar or the same.

Most commonly evaluated parameters of a battery include battery capacity, the ability to store energy; internal resistance, describing current delivery capability; self-discharge, reflecting mechanical integrity and stress-related conditions [1]. Additionally, parameters of interest include discharge curves, showing effective capacity relation to discharge rates; effects of temperature; cycle life, the number of cycles a cell can perform before its capacity drops to 80% of its initial specified capacity; effects of discharge depth on cycle life [3]. Many of these parameters require carrying out comprehensive and time-consuming tests, which can be automated with the use of battery testing equipment.

The market offers battery testing equipment in various price ranges, functionality and measurement accuracy. Examples include:

- The BST8-3, starting with prices of about USD$3000, can concurrently test multiple batteries with configurable voltages and currents. This device is interfaceable with a computer. For additional cost, the functionality of connecting the device with the computer over Wi-Fi can be added [4].
- For less cost, various controllable electronic loads are available [5]. Although these provide less functionality, they can be used to discharge a battery at known rates and thus can be used for example to measure effective capacity relation to the different discharge rates. Typical electronic loads cannot be used to recharge a battery, so separate devices are needed for this purpose.
- Lastly, there are devices such as the Adafruit Charger Doctor, which can measure the capacity of Universal Serial Bus (USB) power banks. These devices do not incorporate electronics neither for charging nor discharging but can measure the amount of charge and discharge that has moved through them. [6]

2.1. System requirements

The battery testing system described in this thesis was developed taking into consideration the suitability for long running tests with moderate charging and discharging currents. The requirements imposed for the design of the battery testing system were:

- User configurable test parameters, allowing to alter:
  - maximum charging current (in the range of 330…2000 mA) and charging voltage (in the range of 3.5…4.4 V, which is sufficient for most single cell Lithium-ion (Li-ion) and Lithium-ion polymer (Li-Po) batteries [7]),
  - discharging current (in the range of 0…4000 mA) and discharging until specified voltage,
  - number of charge-discharge cycles to be conducted.
- Ability to test up to eight batteries concurrently.
- Monitors each battery's:
  - current,
  - voltage,
  - temperature,
  - charge/discharge amount.
- Allows testing batteries in a thermal chamber; the batteries should be connected to the battery tester with long wires enabling to leave the tester outside the chamber.
- Provides convenient way to get measurements onto a PC.
- Configurable safeguards for battery voltage and temperature.
- Fault detection in communication with the PC.
- Live data plotting of an ongoing test and conclusive plots of the test's results.
- Backs up test data onto a Secure Digital (SD) card.

The laboratory thermal chamber allows to test multiple batteries in similar conditions at various temperatures. The capability of measuring the temperature of each battery separately may prove useful in a laboratory thermal chamber test, as different batteries might reach the thermal chamber's specified temperature at different rates. Battery temperature measurements show how charging and discharging affect the battery's temperature, which may be of interest in some applications.

3. Design

3.1. General Structure

The overall structure of the battery testing system is modular. This modularity allowed separate development and testing of the systems individual components. Also, during testing or using the system, in case of a hardware problem with the device, this modularity should make pinpointing and repairing/replacing faulty components easier.

In Figure 1, alongside with laser cut acrylic glass structural elements used to assemble the device, the main components of the battery testing system's hardware can be seen:

1. two 80 mm Arctic F8 PWM fans to provide cooling for the module boards during battery discharge operations;
2. a module board of the battery testing system, up to eight can be connected;
3. Mean Well RSP-200-7.5 power supply (PSU), which provides power to the system;
4. the main board of the battery testing system.

Figure 1. Photograph of the assembled battery testing system

3.2. Electronics design

The main battery testing system's electronics consists of a main board and eight module boards. The electronics schematics and printed circuit boards (PCBs) were designed in Altium Developer 17. Most important electronical components on the main board and module boards, including the types of their interconnecting signals, are shown in Figure 2.
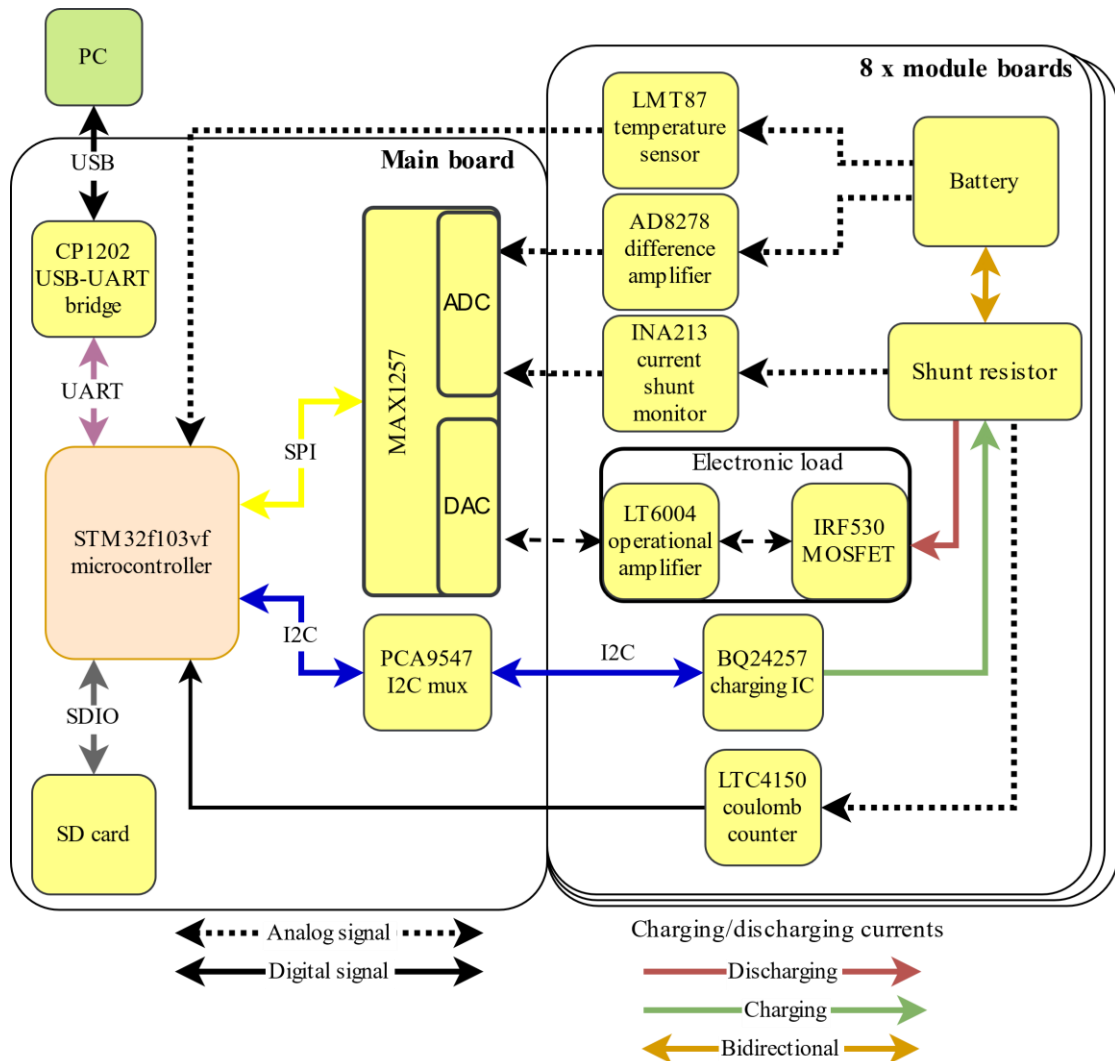

Figure 2. System electronics overview

3.2.1. Module board

Each module board allows to connect a battery to it with a 2x4 Molex connector. The electronics on a module board allow to carry out charging and discharging of the batteries based on the

main board's commands and converts necessary parameters of a battery into suitable form for the main board's analog-to-digital converters (ADCs) to measure. A module board is attached to the main board with a PCI Express x1 connector. All the electronical schematics of the module board can be seen in Appendix 1.

The module boards are designed with two-sided PCBs. Figure 3 shows two module boards, one with a heatsink installed. On the left module board, the layout of the components on the top PCB layer is shown. The tasks handled by grouped components in the figure is as follows: 1. current measurement; 2. charge/discharge monitoring; 3. voltage measurement; 4. charging electronics; 5. discharging electronics. Bottom side of the PCB houses ground (GND) polygon and some signal wires. Note that in squares indicated with 1 and 2 electrical fixes have been made. Square 1 shows an operational amplifier added to the current shunt monitor's reference, and square 2 has a rerouted power wire. These corrections have been included in the module board schematics.
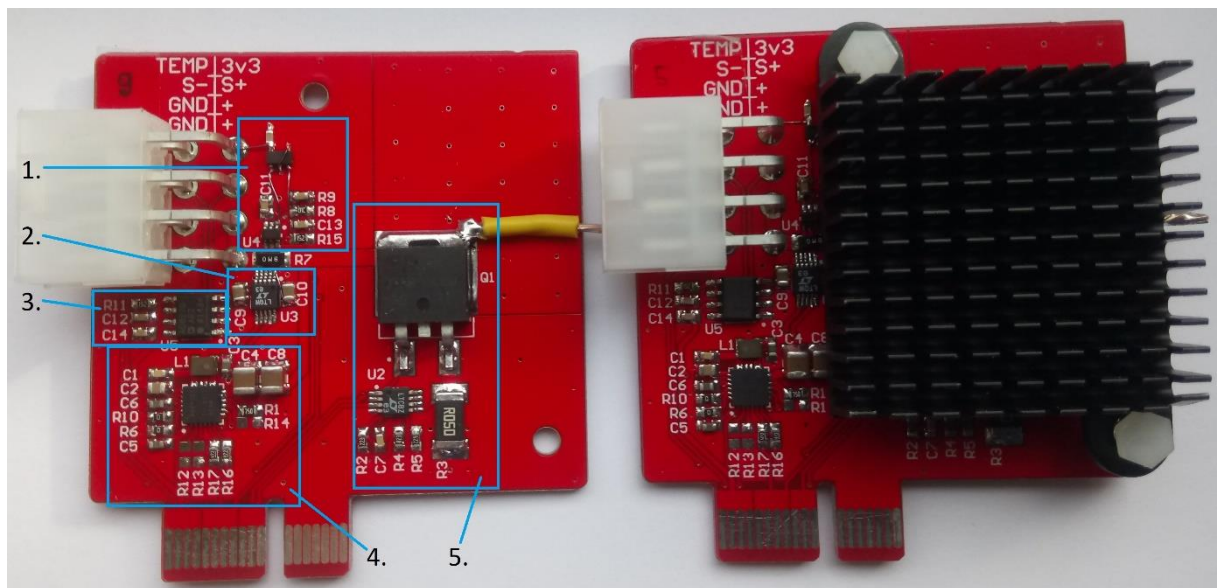
Figure 3. Photograph of module boards' PCB top side

Measurement electronics

The AD8278ARZ difference amplifier, with a gain of ½, is used to scale down battery voltage. A separate pair of wires coming from the battery is used to measure battery voltage without voltage drop on the battery's current carrying wires. The INA213 current shunt monitor's reference voltage has been chosen such that the current shunt monitor can measure 2.05 A of charging current and 4.20 A of discharging current. The difference amplifier's and current shunt

monitor's outputs are measured by the main board's 12-bit ADC with 2.5 V reference, meaning voltage can be measured in the range of 0…5 V with the resolution of 1.22 mV and current with the resolution 1.53 mA.

The LTC4150 coulomb counter is used to keep track of the amount of charge or discharge of a battery. This integrated circuit (IC) monitors current through an external shunt and its internal voltage-to-frequency converter transforms current sense voltage into a series of output pulses at the interrupt pin, which can be captured by the main board's microcontroller unit (MCU). Each pulse at the interrupt pin corresponds to a charge of $\frac{1}{3600 * Gvf * Rsense}$ Ah, where for the LTC4150, the typical value of voltage to frequency gain (G_{vf}) is 32.55 Hz/V [8], meaning with an 8 mΩ shunt resistor (R_{sense}) used on the system, the coulomb counter achieves a resolution of around 1.06 mAh. The polarity pin of the IC gives information in which direction the charge had moved.

For temperature measurements the LMT87 temperature sensor is used. It can be attached to the battery, as the sensor is connected to the battery tester with long wires. The sensor operates in the temperature range of –50…150 °C with the corresponding output range of 3277…538 mV [9]. This voltage is directly measured by the main board's MCU's internal ADC. As the MCU's ADC uses 3 V reference, then the measurable temperature is reduced to the range of -28…150 °C, 12-bit ADC gives the resolution of 0.04 °C per bit.

Charging and discharging electronics

The electronic load schematics was first simulated using LTSpice software. The LT6004 operational amplifiers are used to steer the IRF530 metal–oxide–semiconductor field-effect transistor (MOSFET) according to the main board's analog control signal. The electronic load is designed to be controlled with an analog signal up to 3 V, which allows the electronic load to discharge a battery with the current of 0…4200 mA, meaning with a 12-bit DAC, resolution of around 1.03 mA will be achieved.

To cool the IRF530 MOSFET, firstly thermal vias were added to the 24x30 mm two-sided PCB section the MOSFET is soldered onto. Additionally, an aluminium heatsink with dimensions of 35x35x10 mm can be installed on top of the MOSFET. The heatsink can be seen in Figure 3 on the right module board. During testing at ambient temperature of 25 °C, it was concluded that

the electronic load can continuously discharge an 8.4 W load, then the MOSFET stabilized at temperature of 123 °C. During the test the fans were set to maximum speed and a shroud was placed onto the device to optimize airflow. With these ambient temperatures, 4 A of discharge current can be used for short periods of around 15 seconds. For continuous discharging at high currents the heatsinks should be provided with greater airflow and/or lower ambient temperatures. The MOSFET is rated for maximum operating temperature of 175 °C [10].

The charging operations are handled by the BQ24257 IC, which provides configurable charging currents of 330 mA and 500…2000 mA, with 50 mA steps. Additionally, the IC allows the configuration of charging voltage in the range of 3500…4440 mV, with voltage steps of 20 mV. [11]

3.2.2. Main board

All eight module boards are connected to the main board. The main board controls the module boards and collects measurements of batteries' parameters from the module boards. The main board is intended to be connected to a computer via an USB cable. The MCU uses its universal asynchronous receiver-transmitter (UART) peripheral to communicate with the PC alongside with the CP1202 USB-UART bridge IC. All the electronical schematics of the main board can be seen in Appendix 2.

Microcontroller unit

The STM32F103VFT9 was chosen as the MCU, because of availability and as it had necessary peripherals – UART, Serial-Peripheral Interface bus (SPI), inter-integrated circuit (I^2C) bus, timers, and Secure Digital Input Output (SDIO). This MCU had enough General-Purpose Input-Outputs (GPIOs) and also provided sufficient amount of analog input pins, which are necessary as the MCU's ADC is used for battery temperature measurements.

A timer of the MCU is configured to provide pulse with modulation (PWM) for the cooling fans. The duty cycle of the PWM is configurable in runtime, which in turn allows to control the speed of the fans. The default PWM duty cycle has been configured such that on the start-up of the device both fans are guaranteed to start spinning at low speeds.

The main board also incorporates the micro-SD card connector. The SD card is wired to communicate with the MCU in 4-bit SD transfer mode. The FDC6330L integrated load switch can be used to turn off power for the SD card with an MCU's GPIO, which effectively allows to reset the SD card, should the need arise [12].

External ADC-DAC and I^{2}C multiplexer

The MAX1257 IC's 12-bit analog inputs (16 in total) are used for accurate battery voltage and current measurements. The IC communicates with the MCU over SPI bus. The IC has averaging capabilities [13], it has been configured to output the average of 32 individual measurements. During development it was measured that acquiring 16 ADC readings with averaging takes less than 1 ms. The MAX1257 also incorporates eight 12-bit DAC channels, which are used to control the electronic load used for discharging batteries. The MAX1257's ADC uses its internal 2.5 V reference and the DAC uses external 3 V reference voltage from the ADR363. The same 3 V reference is also used by the MCU's internal ADC.

The PCA9547, an eight-channel I^{2}C multiplexer is used to communicate with module boards' charging ICs. The usage of an I^{2}C multiplexer is necessary because the address of the BQ24257 charging IC is factory set and unchangeable [11], thus the I^{2}C multiplexer makes it possible to still use a single I^{2}C bus.

General PCB layout

The main board is designed onto a four-layer PCB:

1. The top layer (see Figure 4) incorporates (A) fan connectors, (B) eight PCI Express x1 connectors for the module boards, (C) 20-pin JTAG connector for debugging and programming, (D) I^{2}C multiplexer with its signal wires, (E) ADC-DAC, (F) 12 V power regulator, (G) 3.3 V power regulator, (H) crystal oscillator, reset and boot switch for the MCU, (I) micro-SD card connector with its load switch, (J) USB mini-B connector with a 3.3 V regulator and (K) 2x2 Molex connector for the PSU.
2. The first internal layer is mainly ground layer.
3. The second internal layer is used for ADC-DAC signal wires. Using an internal layer for these signals will help to isolate them from noise.

4. The bottom layer incorporates mainly the MCU with its signal wires and the USB-UART bridge IC.
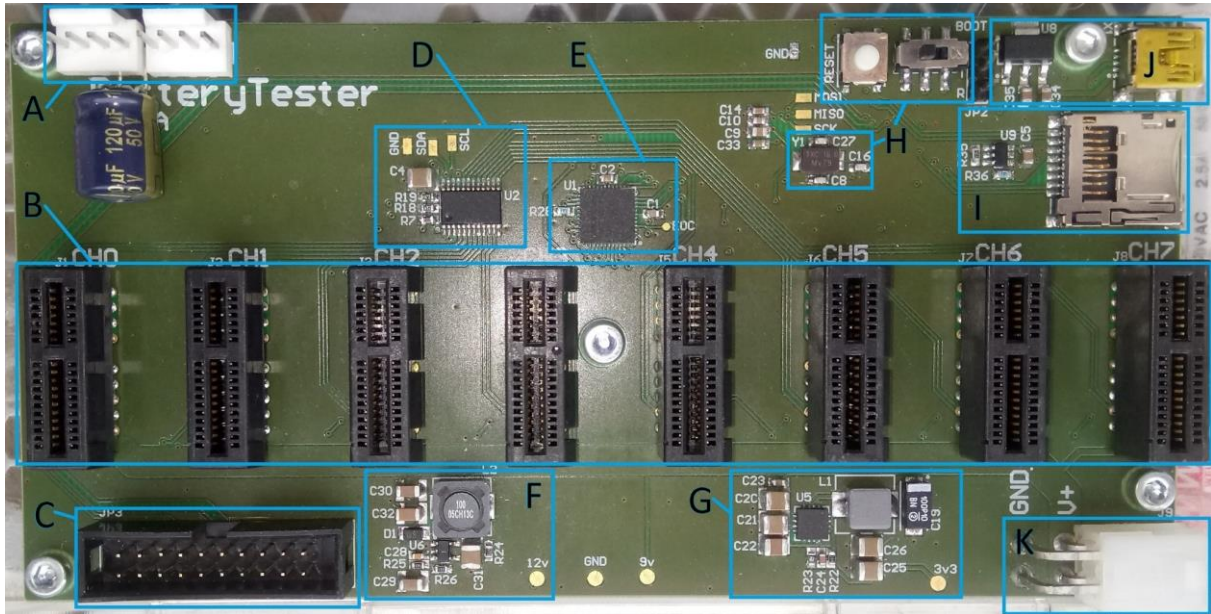

Figure 4. Photograph of main board PCB top side

The main board gets its input power from the Mean Well PSU, which is set to output 6 V. The PSU can deliver 26.7 A of current [14]. The 6 V is fed straight into the module boards' BQ24257 charging IC. Additionally, 3.3 V and 12 V are created on-board. 3.3 V is used by the MCU, external ADC-DAC IC, I^2C multiplexer and SD card, 12 V is used by the cooling fans and module boards' electronic loads. The main board also has circuitry to get 3.3 V from the USB connector, which allowed to test and develop most of the main board's functionality without the PSU.

3.3. Workflow of the MCU

The MCU code was developed in Microsoft Visual Studio Community 2015, with the addition of VisualGDB v5.2R9, which added MCU debugging functionality. Segger J-Link v9.3 was used for debugging and programming.

The MCU will first initialize its internal peripherals and after that goes through the setup of external IC-s. STM32CubeMX was used to generate initialization code and hardware abstraction layer (HAL) for the MCU and its peripherals. The initialization code worked well, apart from the I^2C code, in which the MCU sometimes went into timeout loop and failed the initialization due to the I^2C's analog filter providing a wrong value. The workaround was to configure Serial Data Line (SDA) and Serial Clock Line (SCL) pins to GPIOs, pull them logical low and then high, lastly reconfigure them to I^2C again [15]. The second issue involved timer initialization, which tried to carry out read-modify-write on a write-only register, which resulted in disabling the debugging interfaces of the MCU.
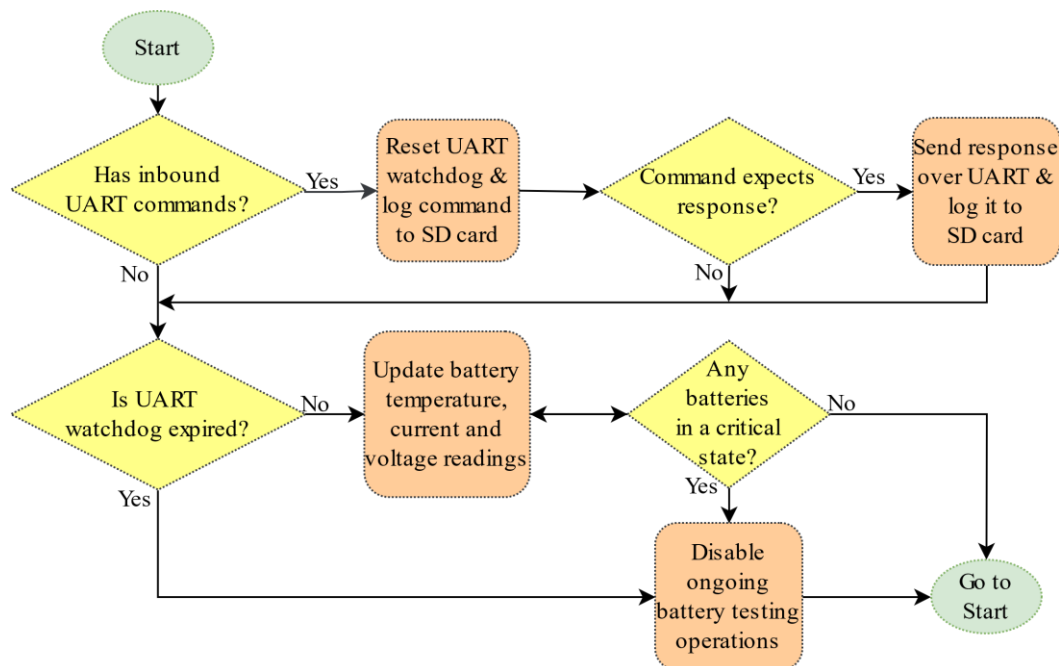

Figure 5. MCU main loop diagram

After initializations, the MCU will go into the main loop as shown in Figure 5. Firstly, the MCU will act upon commands it has received, if necessary prepares a reply and if logging is enabled, writes data to SD card. Inbound UART data validity is also checked with cycling redundancy check – CRC-32. Continuing in the main loop, UART watchdog is checked, if it has timed out, all battery testing operations will be halted. After that, the MCU will update current and voltage readings from the external ADC and averages temperature readings from internal ADC's readings, which are continuously gathered with dynamic memory access (DMA) peripheral. If one channel's temperature or voltage is not in the range of permitted values, that channel's testing operations will be aborted. The range of these permitted values and UART watchdog

timeout are configurable from the PC. The MCU always keeps battery measurements up-do-date so in case a request from the PC is received valid data is always at hand.

3.4. Communication

The UART configuration is as follows: baudrate 500,000; 8 data bits; 1 stop bit; no parity bits. The MCU's UART uses a circular first in, first out (FIFO) buffer for inbound data, the buffer is filled in UART interrupt callback. Outbound UART data is transmitted with DMA.

The communication is set up in the way that the computer sends eight bytes of data to the device. These eight bytes can be commands, e.g. set a specific module board to drain a battery at a specific current; commands do not have replies. The eight bytes can also be requests, e.g. the computer requests a specific module board's battery voltage, current, temperature and coulomb counter data. The lengths of replies can vary dependent on the request. See Appendix 3, for the complete list of all commands/request.

The commands/requests usually are structured as follows: the 1st byte is command code – dependent on that the MCU knows how it's supposed to react, the 2nd byte is usually the index of a module board, the bytes 3 and 4 usually form a value, which is given to the MAX1257 DAC to set up discharging current or to the BQ24257 charging IC to alter charging parameters. The last 4 bytes are CRC-32.

An area of improvement in the communication protocol would be to add Consistent Overhead Byte Stuffing (COB), which would allow to implement commands/requests of arbitrary length. Then for example it would be possible to send initialization parameters in one command.

3.5. Calibration

Calibration data is used to convert physical quantities into values usable for the MCU and for conversions the other way around. Each out of the eight testing channels has its own calibration, 0th channel's calibration is shown in Figure 6. In the figure, voltage, current and temperature calibration plots show the relations to their corresponding physical quantities. Load calibration plot shows what DAC value the MCU expects for a given discharge current. Linear fitting calibration data gave root-mean-squared error values smaller than 0.05.
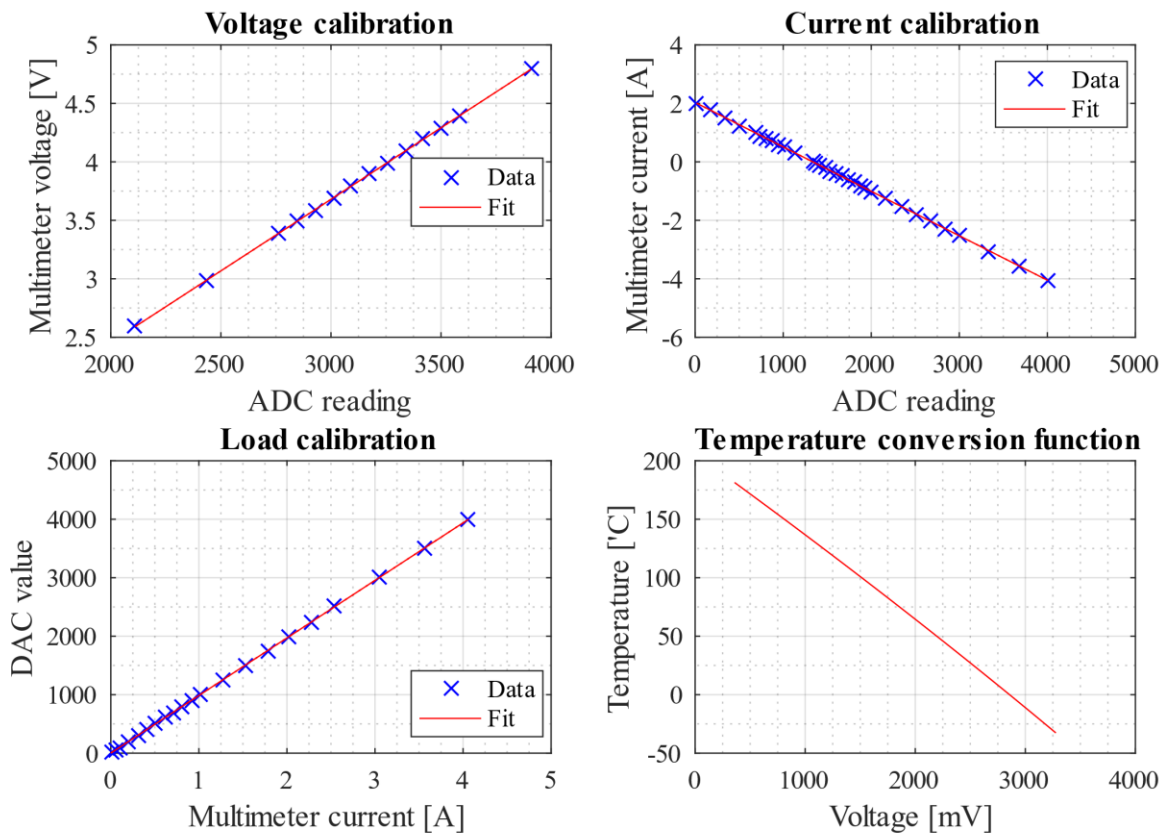

Figure 6. Channel 0 calibration plots

The calibration of the module boards was done using Textronix DMM 4050 multimeter, TTi QL355TP variable lab bench power supply and Mighty Watt electronic load. The devices were controlled, and results were collected and stored using MATLAB R2016a. The temperature conversion is done based on the temperature sensor's conversion function [9] and was not calibrated with other measuring devices.

Voltage calibration setup used the lab bench power supply, providing various voltages in the range of 2.6…4.8 V to the battery voltage sense inputs of the module board. Meanwhile the

multimeter measured the voltages on the same inputs, so with the main board ADC's voltage readings the voltage calibration was created.

Data for load calibration and current calibration discharge part were collected at the same time. For that the multimeter, the lab bench power supply and the tester's module board were connected in series. The module board's electronic load was used to set an amount of discharge current and hold the current until measurements were collected, then the current was increased, and the process repeated; current range of 0…4 A was used. The charging part of the current calibration was done using MightyWatt electronic load that simulated various charging currents passing through the module board's current measuring shunt resistor, whilst the multimeter and the main board's ADC were measuring the current.

3.6. Data logging onto SD card

The logging capabilities of the device were tested with the Silicon Power 8 GB Elite UHS-1 SD card [16], which was formatted in FAT32 file system with cluster size of 4 KiB. The microcontroller uses a generic FAT/exFAT filesystem module [17] called FatFs for creating log files, writing and synchronizing the log files. Special attention of the synchronization operation was given as this operation ensures that data from buffers has been written to the SD card [18], but it also hinders performance as shown in Table 1. Based on the table, the synchronization was set to take place periodically after 200 bytes.

Table 1. Writing 300,000 bytes to a file, in blocks of 10 bytes

Synchronization operation after	Average write speed	Average time to write 10 bytes
Never	42492 bytes/s	~ 0.24 ms
100 bytes	8551 bytes/s	~ 1.17 ms
200 bytes	13717 bytes/s	~ 0.72 ms

Data is written to the SD card in ASCII. For each command or request from the PC, the logged data includes: time, the command/request code and in case of a request also the reply. The data logging timestamp's resolution is set to 10 ms. The MCU uses STM32CubeMX HAL's SysTick

to keep track of elapsed time. To counter the SysTick's possible drift, the PC should periodically send a time update. The timestamp logged onto the SD card consists of two values:

1. PC time since the start of a test,
2. MCU measured time since the PC sent its time update.

The logged data is sufficient to reread and recreate the test results. It was observed, that MATLAB serial library's capability to sending a command over UART and getting a reply took about 100 ms. At most 69 bytes of data (see Appendix 3 – Table 4) is written to the SD card for reacting to a command, which means an 8 GB SD card should be sufficient to log data for over 3000 hours.

4. Results and testing

4.1. Coulomb counter accuracy test

Two 30-minute tests were conducted to see the accuracy of the battery tester's on-board coulomb counter IC, see Table 2 for the results. The tests were conducted at fixed discharge currents with measurements taken every 10 seconds. Later the currents gathered by multimeter and tester were used to calculate the discharge amount in mAh. The calculation involved integrating the currents with the trapezoidal rule and dividing the integral by 3.6 to convert coulombs to mAh. In the end of the 30-minute test runs, both the coulomb counter IC's result and tester current integral were less than 1.1% off from the multimeter measured current integral.

Table 2. 30-minute coulomb counter drain test

Tester set drain current [mA]	DMM 4050 multimeter measured current integral [mAh]	Tester measured current integral [mAh]	Coulomb counter drain amount [mAh]
500	249.0	249.2	251.7
750	372.8	371.0	375.5

4.2. User interface

The PC software, which allows to control the device, is written in MATLAB R2016a. MATLAB scripts provide means to connect and communicate with the battery testing system, and to store and plot data acquired from the testing device.

Ready-to-run scripts are provided, which allow users to specify the voltage bounds in which specific batteries will be tested, charging and discharging currents. These scripts allow to configure the number of charge-discharge cycles that will be conducted or allow to set the time during which batteries will be cycled. The scripts check user-configurable parameters and the user will be warned if any of the parameter is out of reasonable or unsupported bounds.

Live plotting features were added to the MATLAB scripts to allow monitoring an ongoing test. The live plots' time window length is user-configurable. Battery tester's channels 0 and 5 live data plots during discharge are shown in the Figure 7, the respective channel's results are arranged columnwise. The script was configured to update current and voltage at maximum frequency, coulomb counter data i.e. charge and discharge information every 5 seconds and temperature every 16 seconds. Rowwise the plot contains:

- The first row's subplots depict voltages with blue lines and currents with red lines, negative currents represent discharging. The units are volts and amperes respectively.
- The second row's subplots depict coulomb counter readings, where the green line shows charging and the red line discharging in milliamp-hours.
- The third row's subplots depict temperature sensor readings in Celsius scale.
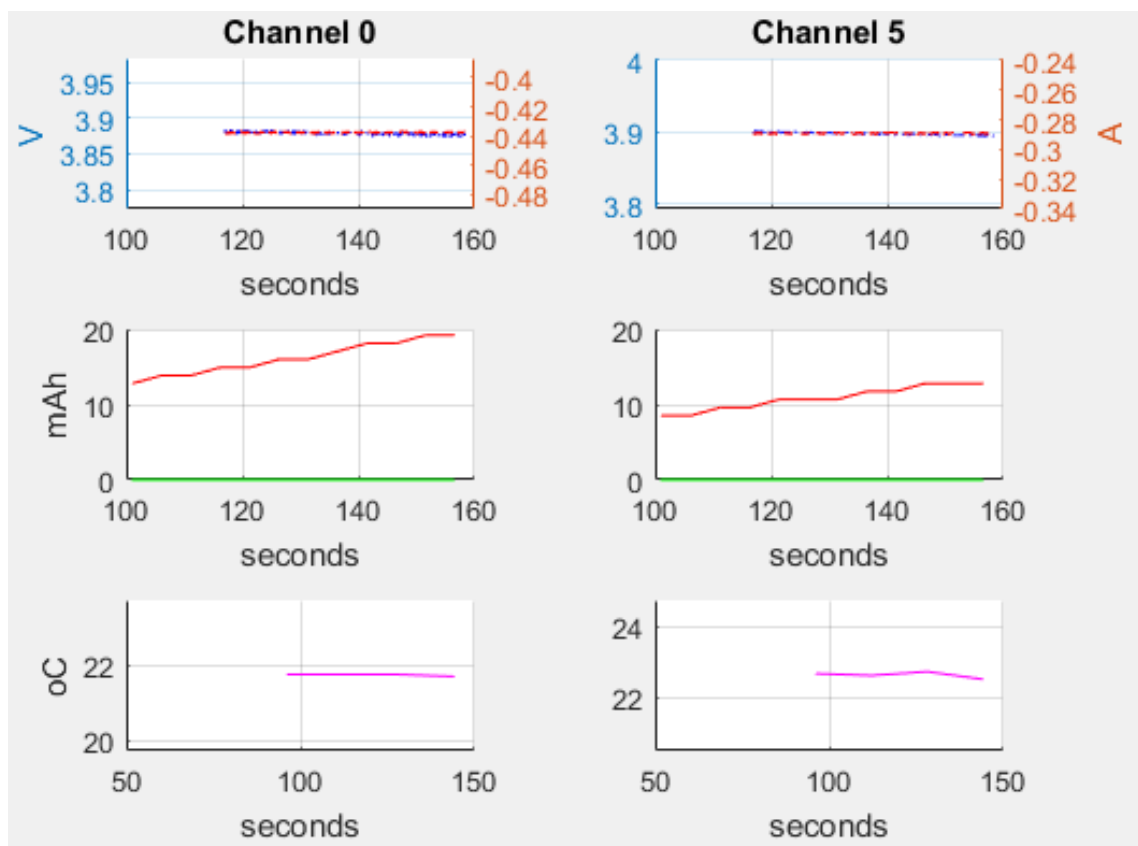

Figure 7. Two battery test live plot screenshot

When a test ends or SD card backup data is read, the MATLAB script opens an interactable plot for each channel that underwent a test, an example can be seen in the Figure 8. In the example the battery was discharged and recharged two times, with the currents of -0.5 and 0.5 A respectively, within the voltage range of 3.7 V to 4.1 V. To analyze a timeframe of interest, a subplot can be zoomed in, the other plots' time scales will also adjust accordingly. The subplots' locations and coloring scheme is the same as the live plot's.
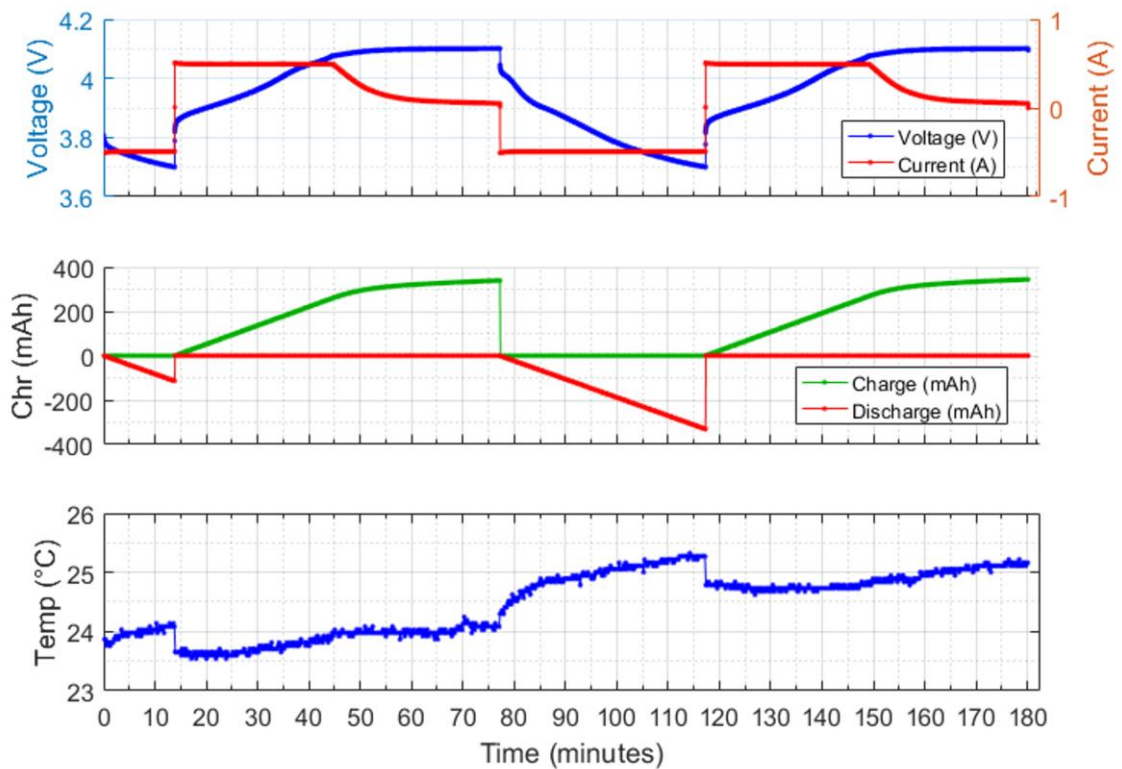

Figure 8. Battery cycling test results

Depending on the need, the user can modify or create new MATLAB scripts, using the provided code to communicate with the device and to plot collected data. This allows to conduct tests with different parameters and purposes. The user can choose which data is plotted and acquired from the battery tester. The MATLAB functions also provide means to set battery tester's configurations and override battery protection parameters, in case the user wishes to perform destructive battery tests.

Summary

The aim of this thesis was to develop a multichannel battery testing device that allows to test batteries in a laboratory thermal chamber. The battery tester's requirements were chosen to accommodate testing single cell Li-Po and Li-ion batteries. The hardware on the resulting prototype is fully functional and the software allows to conduct different user-configurable tests and presents the results in various graphs. Up to eight single cell batteries can be tested concurrently. Most important aspects of the battery tester prototype were:

- able to measure voltage (range of 0…5 V), current (range of -4…2 A), temperature (range of –28…150 °C), monitors the amount of charge/discharge;
- charging current range of 0.33…2 A and discharging current up to 4 A;
- protecting the batteries against undervoltage, overvoltage and overtemperature;
- logs backup data to an SD card, which can be used to reproduce the test results.

The electronics of the battery testing device were divided onto a main board and eight module boards. One battery can be connected to each module board. A module board can charge-discharge a battery and provides necessary conversions for the main board to conduct measurements of the battery. The MOSFET based electronic load on the module board is controlled by the main board's external DAC. For charging operations, module boards have highly integrated and configurable charging ICs.

The main board is responsible for communicating with the computer, controls and collects measurements from the module boards. Voltage and current measurements are done using an external ADC. Temperature measurements are conducted by the main board MCU's internal ADC. The external ADC and DAC are used for improved accuracy and precision.

The microcontroller's internal peripheral initialization code and hardware abstraction layer was generated with STM32CubeMX. Code to control external integrated circuits was written in C language. Computer side software was developed in MATLAB R2016a, this software is used to communicate with the device and to plot test results. Users can write new MATLAB scripts or configure existing ones, to create suitable tests with different parameters and purposes.

Kokkuvõte

Käesoleva bakalaureusetöö eesmärgiks oli välja töötada labori termokapis kasutatav akutestimissüsteem. Seade on välja töötatud kaheksa üheelemendiliste Li-ioon ja Li-Po aku samaaegseks testimiseks. Valminud akutestimissüsteemi riistvara on töövalmis ning arvutipoolne tarkvara võimaldab läbi viia erinevaid seadistatavaid teste. Käimasolevate testide seisu kuvatakse reaalaja graafikutel, lõplikud testide tulemused kuvatakse kokkuvõtvatel graafikutel. Olulisemad süsteemi parameetrid:

- võimeline mõõtma akude pinget (vahemikus 0…5 V), voolu (vahemikus -4…2 A), temperatuuri (vahemikus (-28…150 °C) ning jälgima akude laetuse/tühjenemise taset;
- laeb akusid vooludega vahemikus 0.33…2 A ja tühjendab vooludega kuni 4 A;
- kaitseb akusid alalaetuse, ülelaetuse ja kõrge temperatuuri eest;
- logib tagavaraandmed SD kaardile, millega saab testi tulemused taastada.

Akutestimissüsteemi elektroonika on jaotatud peaplaadi ja kaheksa moodulplaadi vahel. Iga moodulplaadi külge saab ühendada ühe aku. Moodulplaadi elektroonika võimaldab akut täis ja tühjaks laadida ning teisendab akude mõõdetavad parameetrid peaplaadi jaoks mõõdetavasse vormi. Akude tühjendamiseks kasutakse väljatransitori baasil ehitatud koormist, mida juhib peaplaadi mikrokontrolleri väline digitaal-analoogmuundur. Laadimiseks on moodulplaadid spetsiaalne integraalskeem.

Peaplaadi ülesanneteks on arvutiga suhtlemine ja moodulplaatide juhtimine ning nendelt mõõtetulemuste kogumine. Voolu ja pinge mõõtmised teostatakse mikrokontrolleri välise analoog-digitaalmuunduriga, temperatuuri mõõdab mikrokontrolleri seesmine analoog-digitaalmuundur. Mikrokontrollerist eraldiseisvaid muundureid kasutatakse täpsemate mõõtetulemuste saavutamiseks.

Mikrokontrolleri initsialiseerimiskood ja riistvara abstraktsioonikiht genereeriti STM32CubeMX tarkvaraga. Akutestimisüsteemi mikrokontrolleri programm on kirjutatud C keeles. MATLAB R2016a abil kirjutatud arvutipoolne tarkvara võimaldab testseadmega suhelda ja testi tulemusi kuvada. Olemasolevaid MATLABi skripte muutes või uusi kirjutades on võimalik luua nõuetele vastav sobilike parameetritega ning eesmärgiga test.

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Appendices

Appendix 1.   Module board schematics
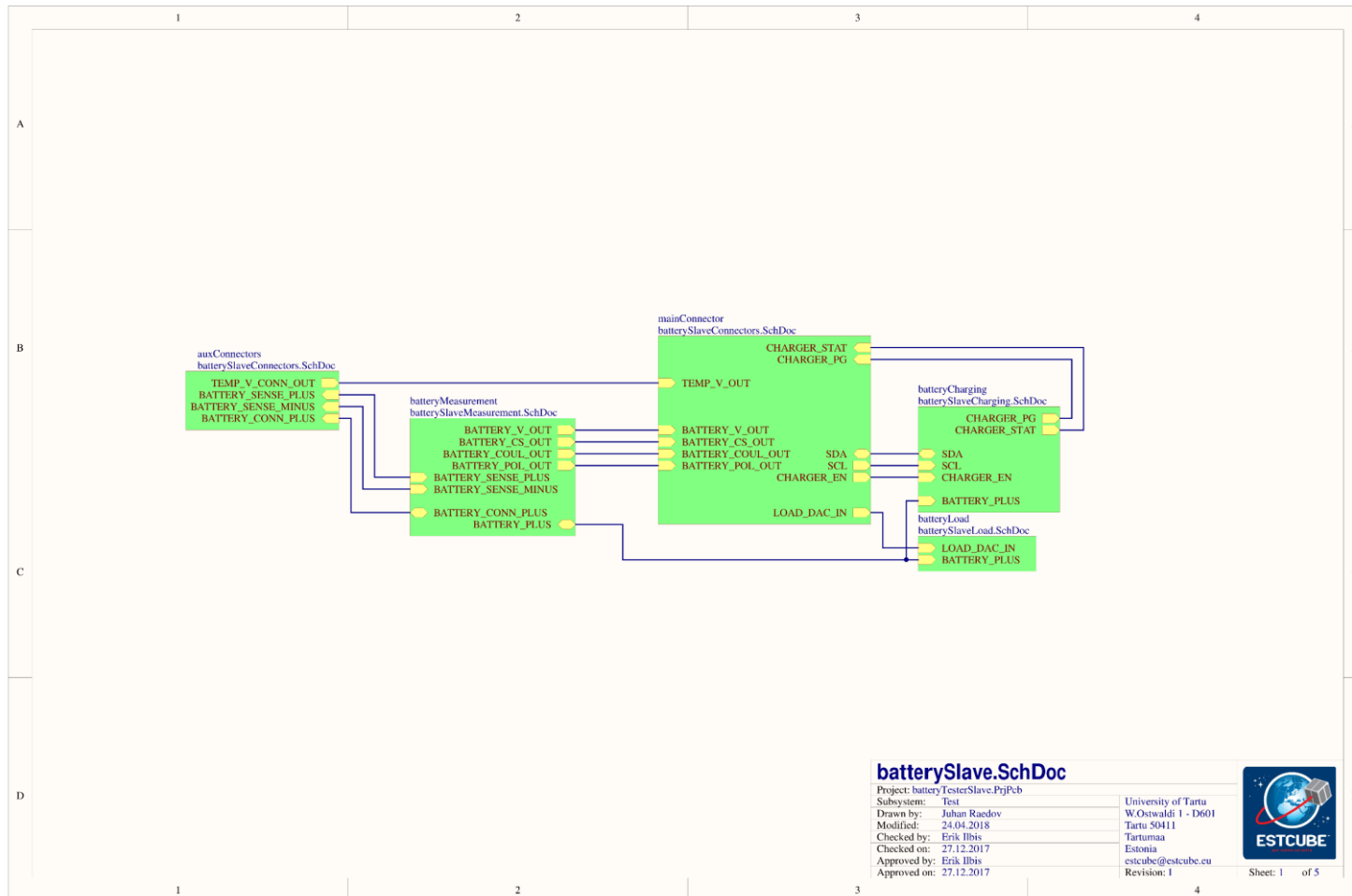
Figure 9. Module board main schematics sheet
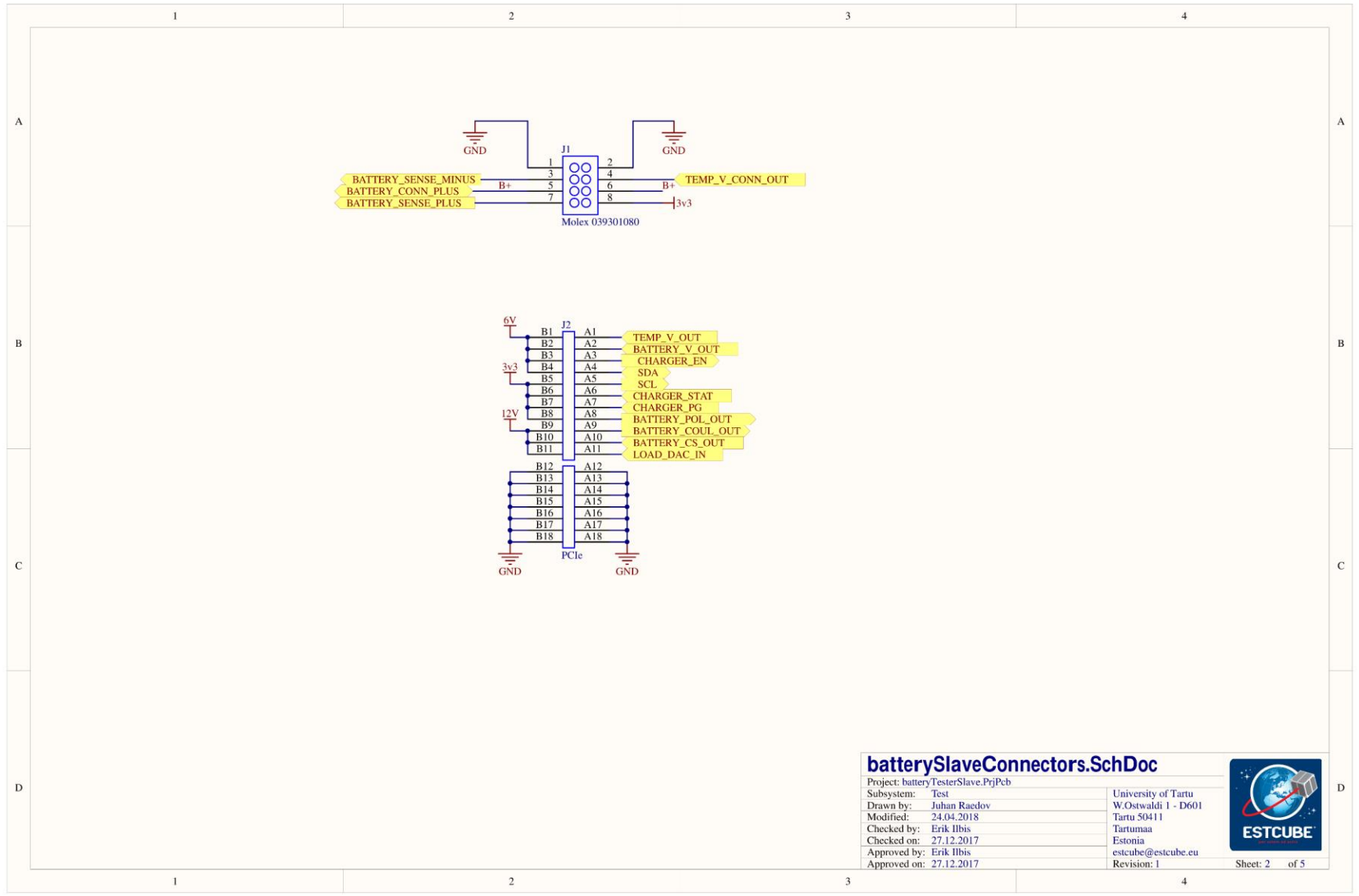
Figure 10. Module board connectors schematic
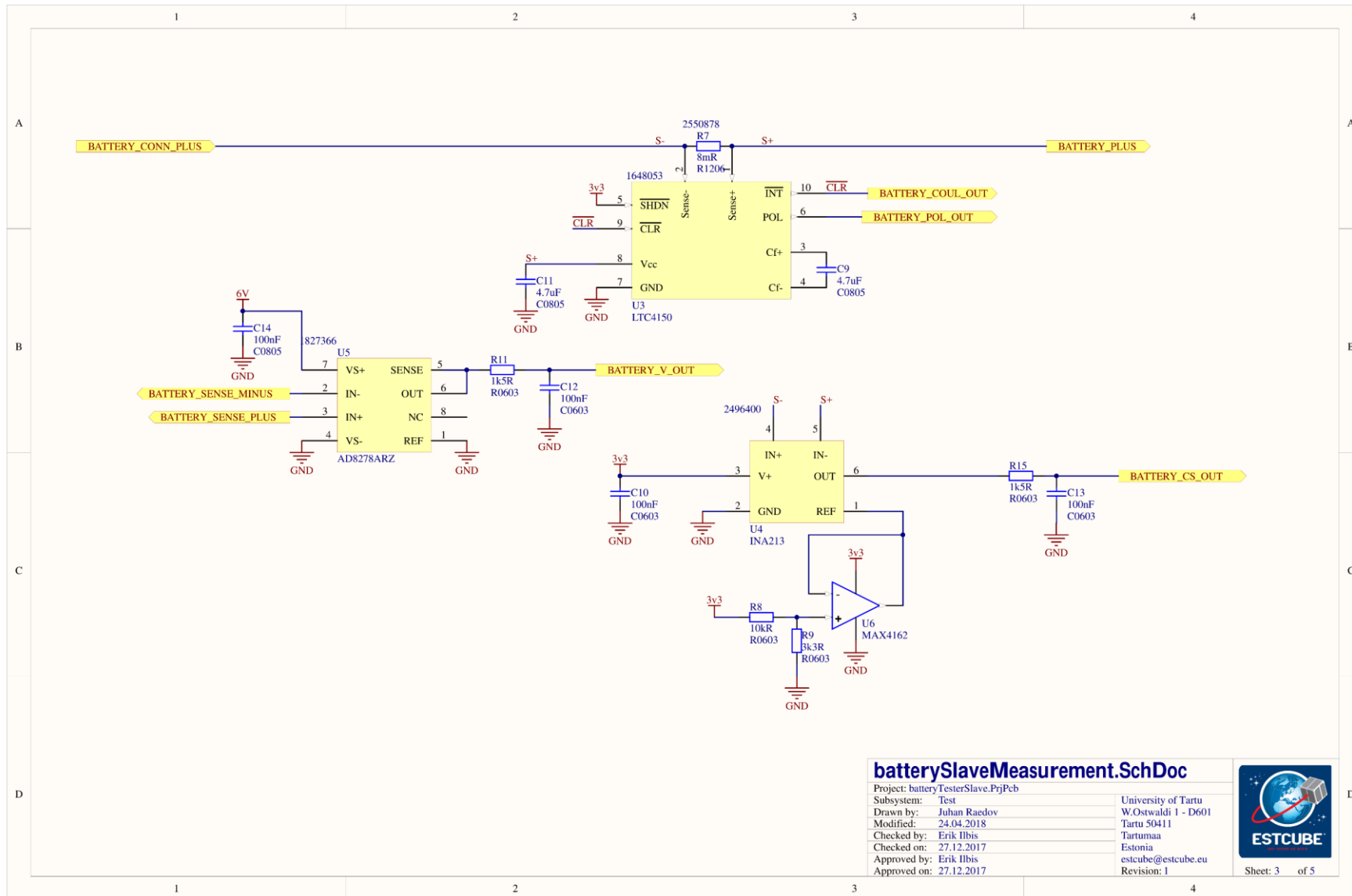
Figure 11. Module board measurement electronics schematics

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Figure 12. Module board charging electronics schematics
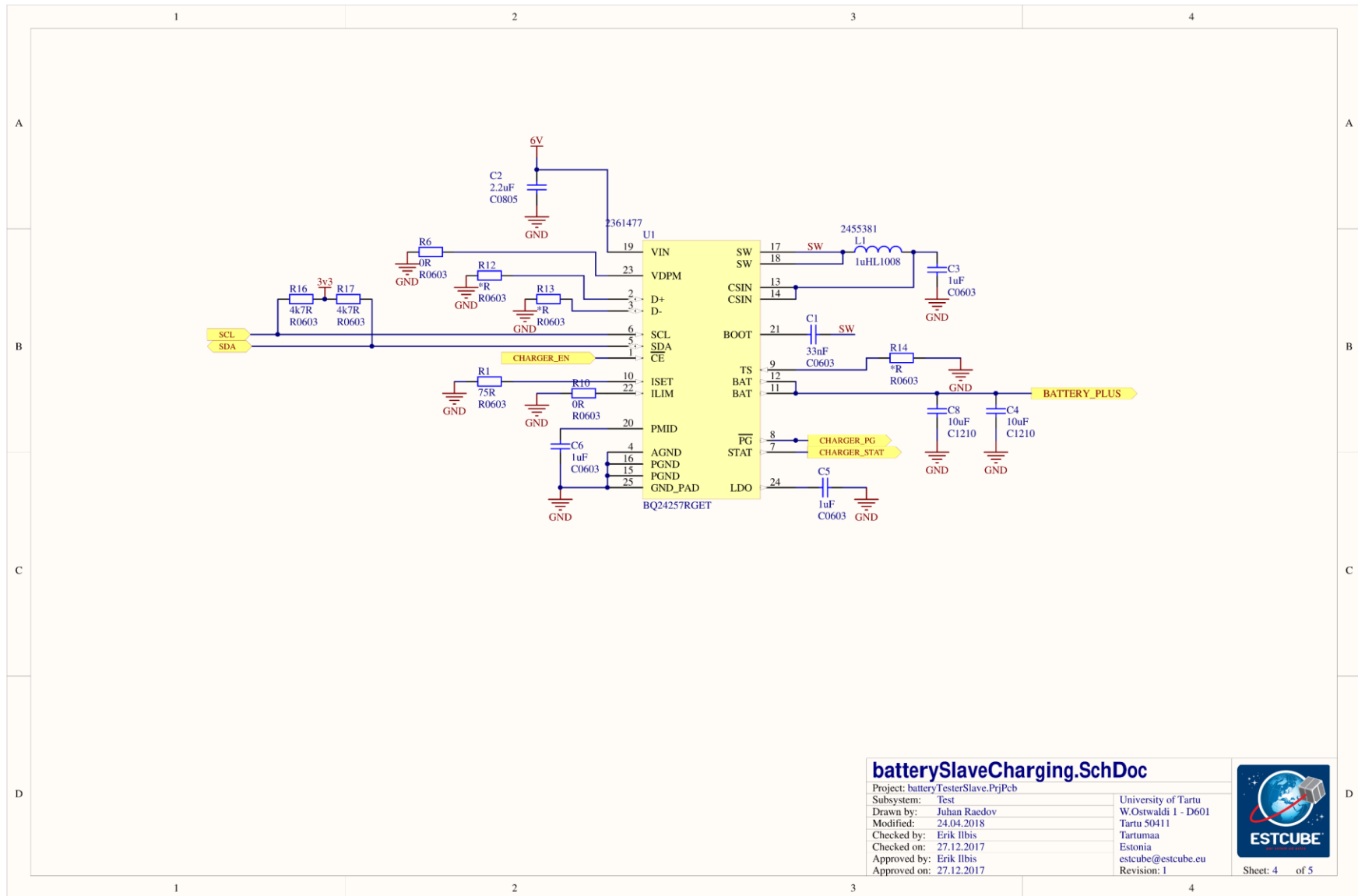
Figure 13. Module board electronic load schematics

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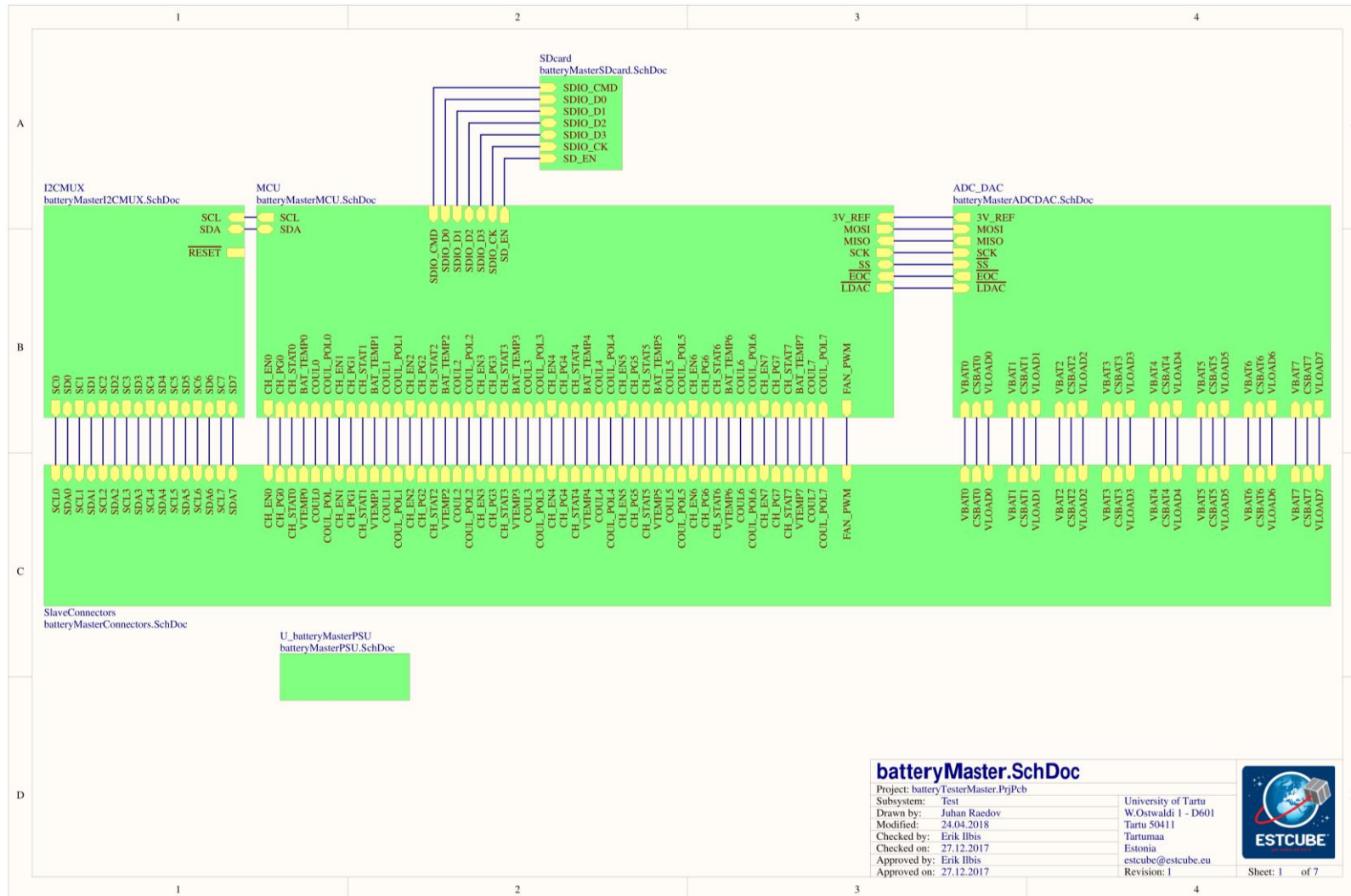# Appendix 2.   Main board schematics
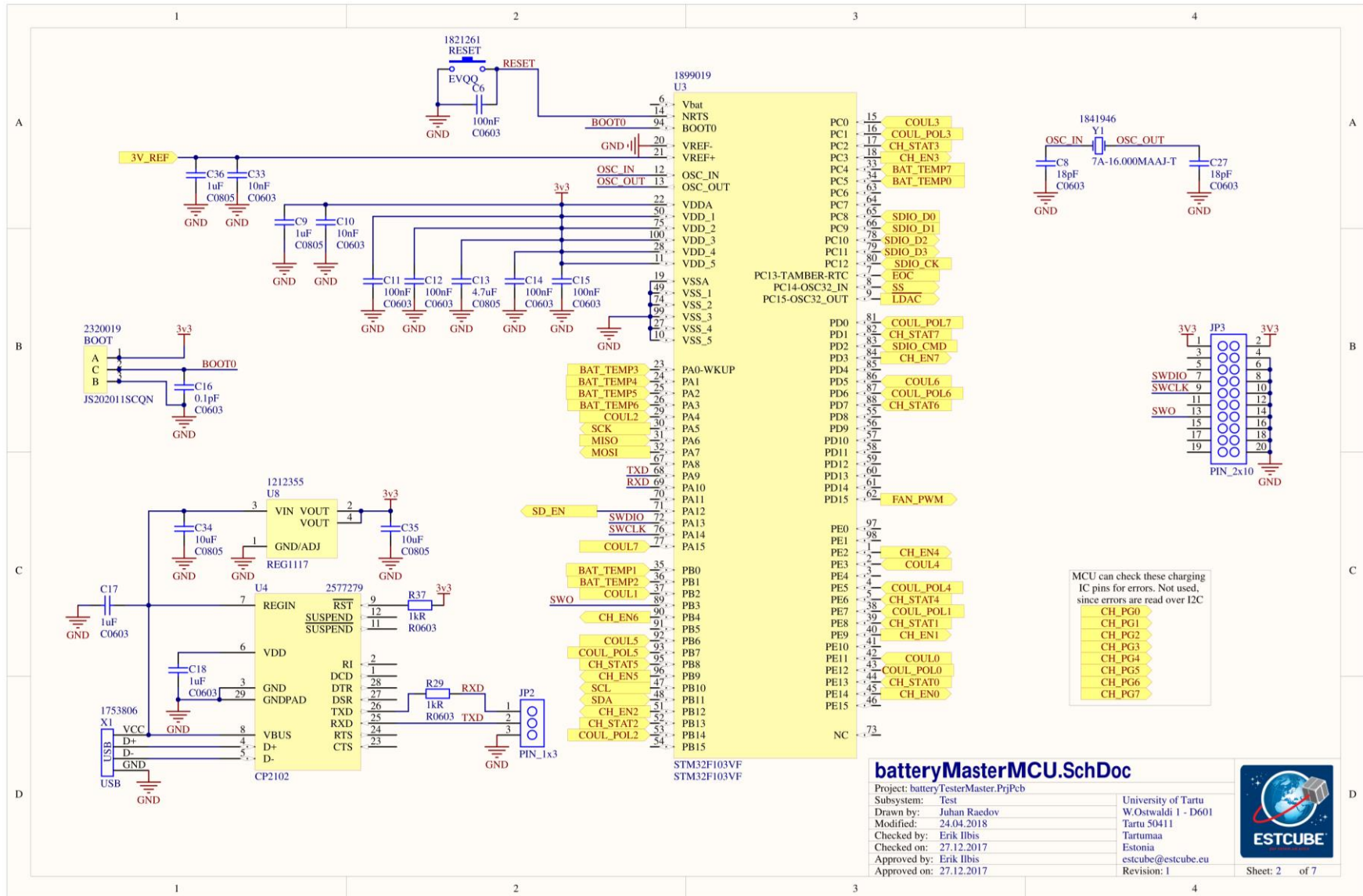

Figure 14. Main board main schematics sheet

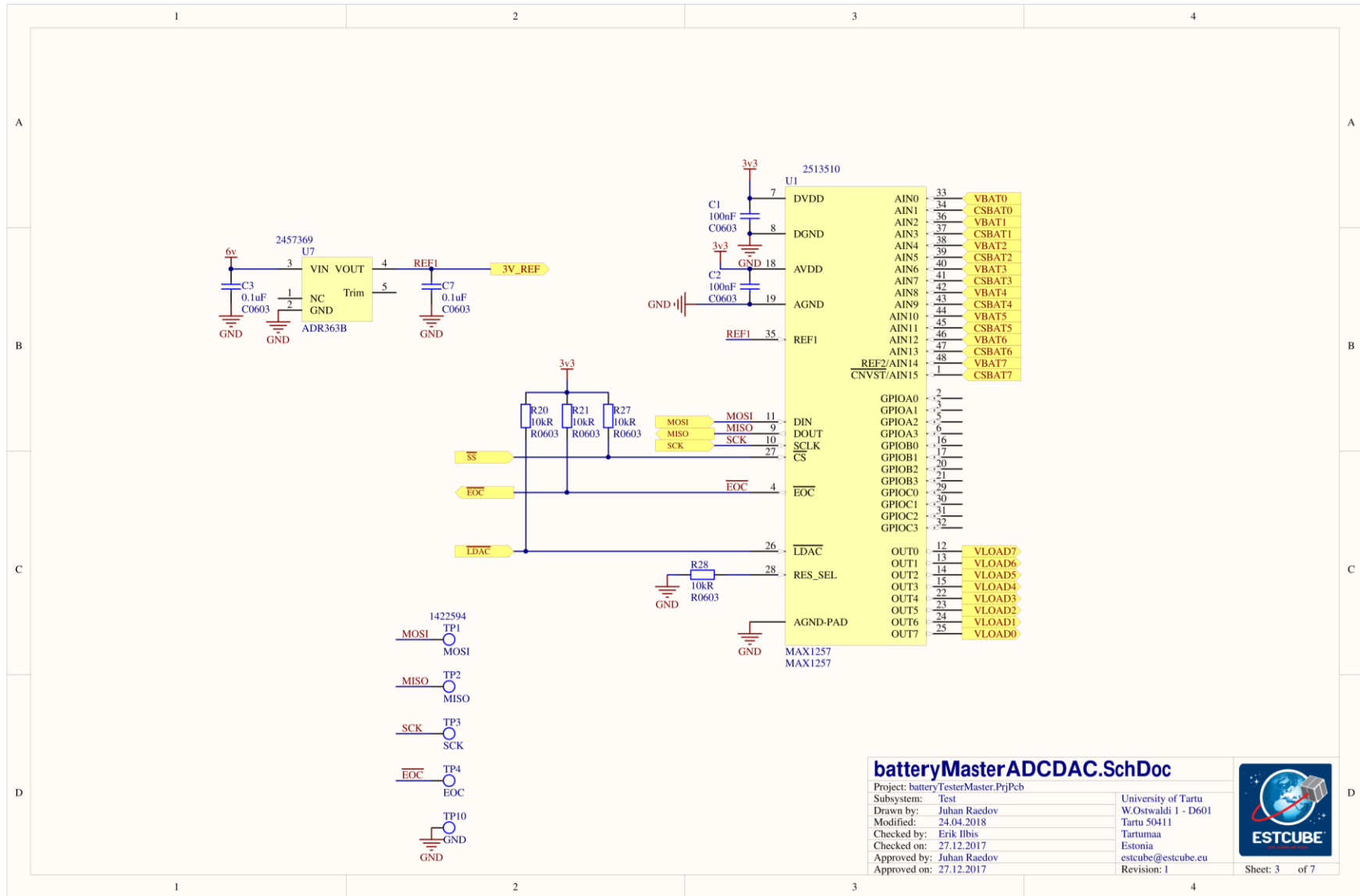Figure 15. Main board MCU schematics

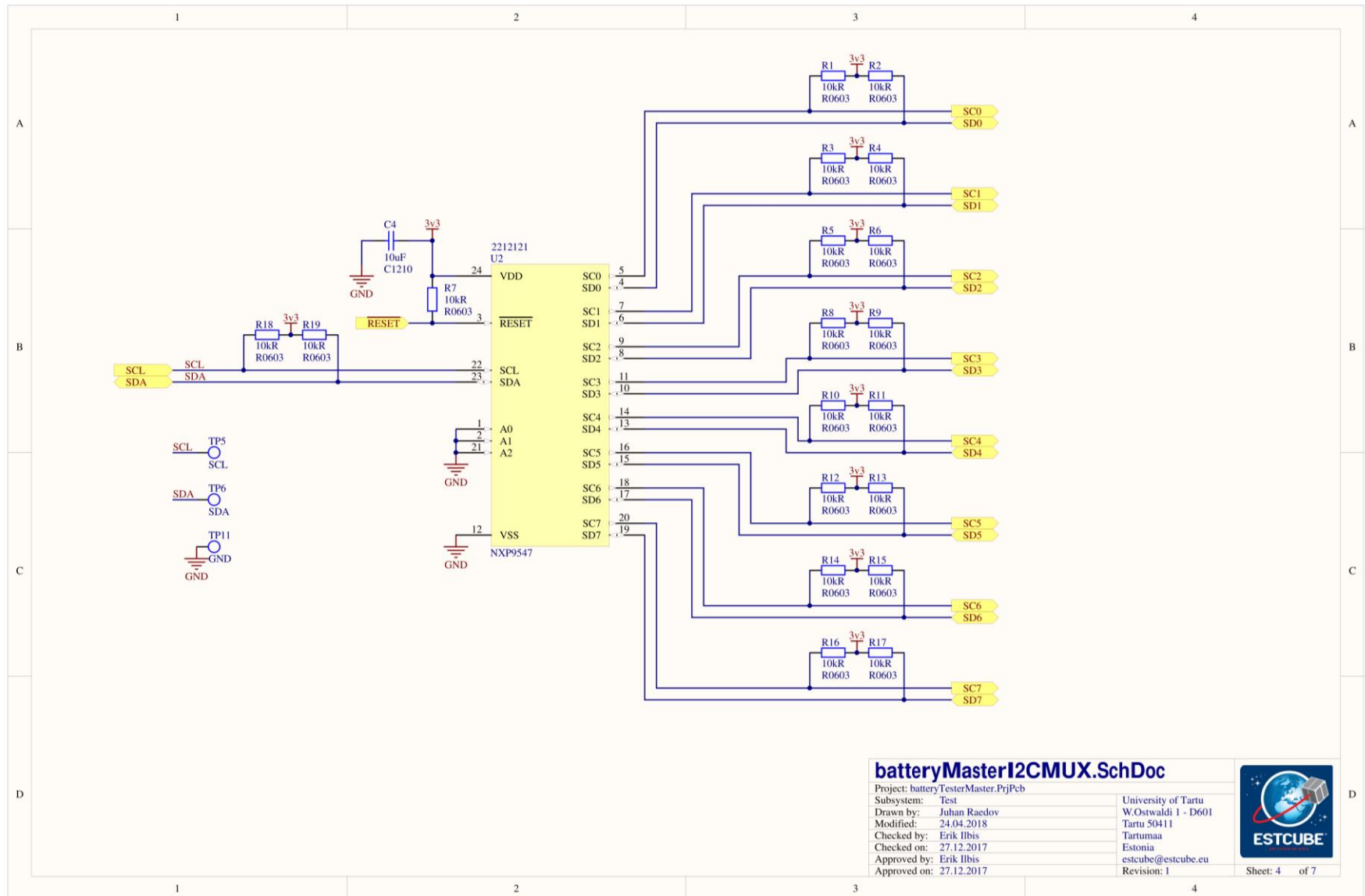Figure 16. Main board ADC-DAC schematics

Figure 17. Main board I2C multiplexer schematics

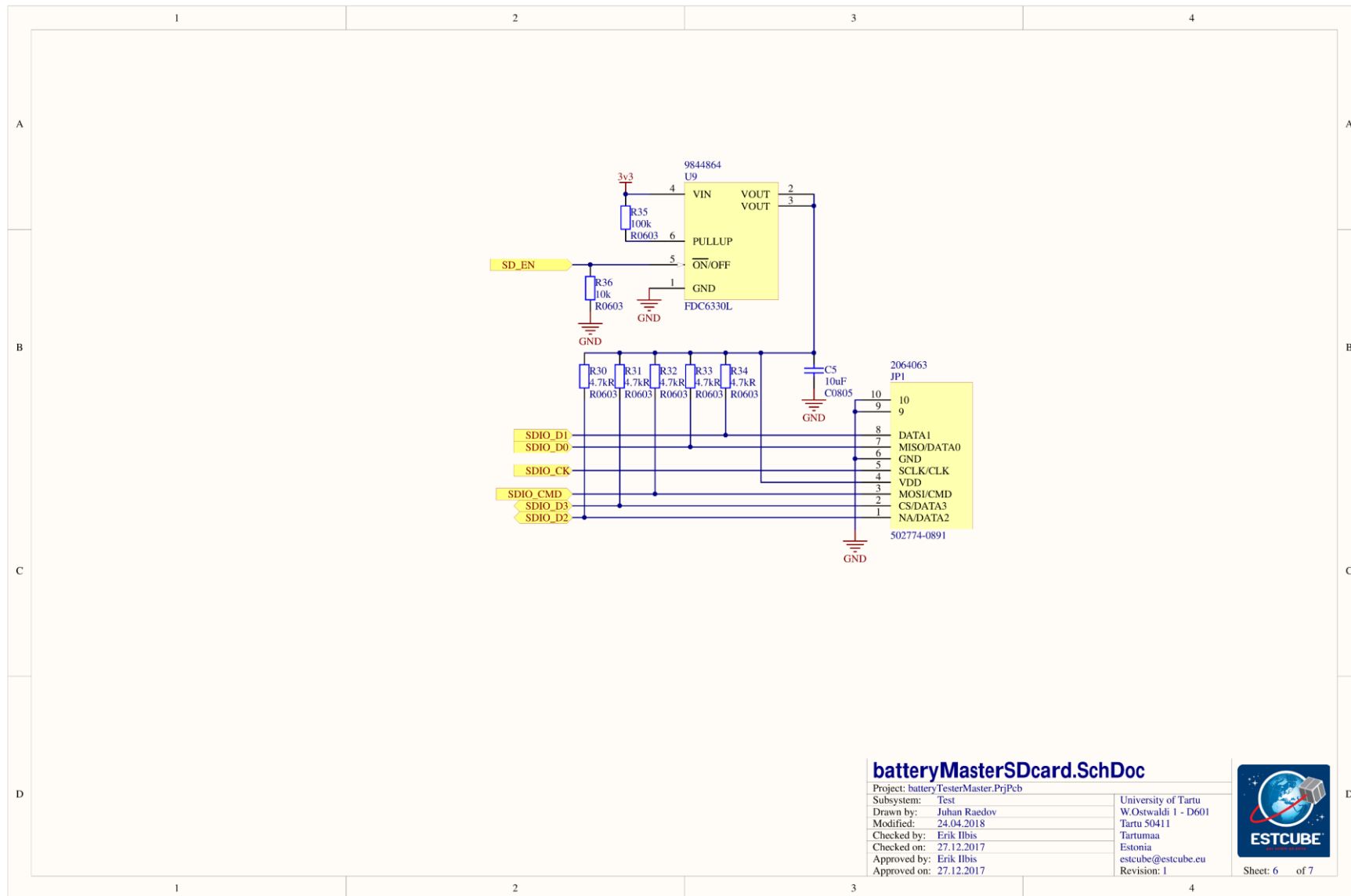Figure 18. Main board connectors schematics 40
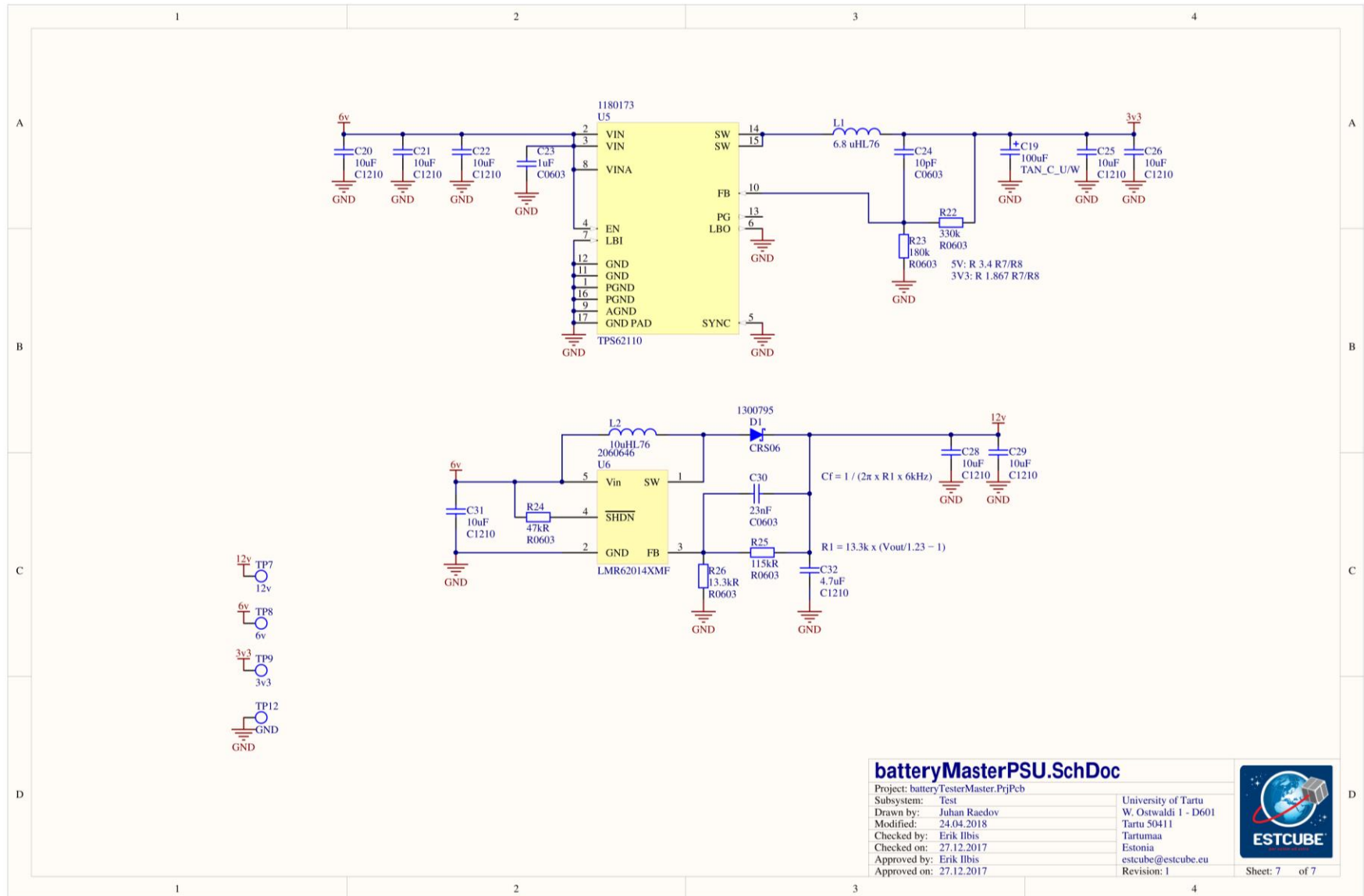
Figure 19. Main board SD card schematics

Figure 20. Main board power management schematics   42

Appendix 3.   Communication protocol

Table 3. System and channel initialization commands

	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply
System & channel initializations	System initialize	Initialized	130				Forbids charging, discharging, reinitializes MAX1257, deinitializes channels	None
	Set fan duty cycle	25%	131		percentage			None
	Init channel	Initialized	140	channel			Disable discharging, initializes BQ2547 (charging is disabled)	None
	Deinitializes channel	Initialized	141	channel			Disables channel operations, status set to not initialized	None
	Set UART heartbeat timeout	5000 ms	142		milliseconds		Disables charging & discharging if timeout. 0 disables heartbeat	None
	Set battery recognition voltage	3000 mV	143		voltage mV		Initialization fails, if under rec. voltage	None
	Set battery critical low voltage	3600 mV	144		voltage mV		Disables discharging if undervoltage	None
	Set battery critical high voltage	4250 mV	145		voltage mV		Disables charging if overvoltage detected	None
	Set battery critical high temperature	1958 mV (50 °C)	146		value (mV / °C)		Disables operations if high temp. See LMT87 transfer table	None
	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply

Table 4. Measurement and status commands

Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8	Byte 9	Byte 10	Byte 11	Byte 12
Get channel status & measurements		150	channel				Yes	13	150	channel	status	voltage		current		charged		discharged		Temperature	
Reset channel measurements		151	channel				None														
Get multiple channel statuses		152	Bit as chn[1] index			0xFF - all channels, 0x01 - channel 0	Yes	1+n	152	0 chn status	1 chn status	2 chn status	3 chn status	4 chn status	5 chn status	6 chn status	7 chn status				
Get multiple channel voltages		153	Bit as chn index				Yes	1+2*n	153	0 chn voltage		1 chn voltage		2 chn voltage		3 chn voltage		4 chn voltage		...	
Get multiple channel currents		154	Bit as chn index				Yes	1+2*n	154	0 chn current		1 chn current		2 chn current		3 chn current		4 chn current		...	
Get multiple channel charge tics		155	Bit as chn index				Yes	1+2*n	155	0 chn charge		1 chn charge		2 chn charge		3 chn charge		4 chn charge		...	
Get multiple channel discharge tics		156	Bit as chn index				Yes	1+2*n	156	0 chn discharge		1 chn discharge		2 chn discharge		3 chn discharge		4 chn discharge		...	
Get multiple channel temperatures		157	Bit as chn index				Yes	1+2*n	157	0 chn temp[2]		1 chn temp		2 chn temp		3 chn temp		4 chn temp		...	
Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8	Byte 9	Byte 10	Byte 11	Byte 12

[1] Chn – channel
[2] temp - temperature

Table 5. Charging integrated circuit commands

	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8	Byte 9
BQ24257 charger	Enable charging	Disabled	160	channel			Disables discharging	None											
	Disable charging	Disabled	161	channel			Disables discharging	None											
	Set channel charge voltage	4200 mV	162	channel	voltage mV		3500...4440mV, step 20mV	None											
	Set channel charge current	500 mA	163	channel	current mA		500...2000mA, step 50mA	None											
	Set channel charge termination current	50 mA	164	channel	current mA		50...200mA, step 25mA	None											
	Get BQ24257 internal registers		165	channel				Yes	10	165	channel	Code	reg1	reg2	reg3	reg4	reg5	reg6	reg7
	Enable multiple channel charging	Disabled	166	Bit as chn index			Disables discharging	None											
	Disable multiple channel charging	Disabled	167	Bit as chn index			Disables discharging	None											
	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8	Byte 9

Table 6. MAX1257 ADC-DAC and SD card logging commands

	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3
MAX1257 ADCDAC	Reset MAX1257		180				Doesn't update battery status	None					
	Control discharging	0 mV	181	channel	voltage mV		12-bit value; disables charging	None					
	Update MAX1257 readings		182					None					
	Set MAX1257 auto-update	enabled	183	0 - disable, 1 - enable				None					
	Get MAX1257 conversion index, data age		184				If age is greater than 255 ms, then 255 ms will be shown	Yes	4	184	Age ms	Conversion index	
	Control multiple channel discharging		185	Bit as chn index	voltage mV		12-bit value; disables charging	None					
	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3
SD logging	Enable logging (update logging time)		190	Time				None					
	Stop logging		191					None					
	Get logging status		192					Yes	2	192	status		
	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3
	Clear RX FiFo						In case of CRC error	Yes	1	230			
	Unknown command							None					
	Command & description	Default	Byte 0	Byte 1	Byte 2	Byte 3	Remarks	Reply	Nr of Bytes	Byte 0	Byte 1	Byte 2	Byte 3

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