Industrial immersion report

Sergei Vostrikov

August 29, 2018

Contents

1 Introduction

Nowadays wearable technologies are being developed rapidly bringing solutions for a growing variety of applications such as health and performance monitoring, smartwatches. One of the most critical constraints that slow the development of this area is a power supply. Today batteries are not effective enough to power all electronics that can theoretically be used in wearable devices for the desired time interval. A promising alternative for traditional rechargeable power systems is systems that contain body heat energy harvesters for battery charging. Such harvesters transform thermal flux flowing from the skin surface to ambient air into electric power due to thermoelectric effects. Interest to this area has been significantly increased during last years that publication activity confirms. Nowadays experimental wearable low gradient thermoelectric generators have the power density of tens $\mu W/cm^2$. To make them suitable for powering modern devices with RF transmitters the power density should be increased approximately by a factor of ten to reach the milliwatt range of total generated power. The most challenging issues that should be solved for increasing TEG's efficiency are:

1. Creating new thermoelectric materials with a higher figure of merit ZT,
2. Minimizing thermal resistance of cold side heat exchanger,
3. Minimizing skin to TEG thermal resistance,
4. Creating effective low voltage DC-DC converters,
5. Creating a thorough mathematical model for TEG design optimization.

Some of these problems can be solved purely theoretically, but to validate the models and proof the concepts an experimental facility that imitates processes in wearable TEG is needed.

2 Aim

The aim of the Industrial Immersion practice is to design and create an experimental facility that would be able to imitate heat exchange, thermoelectric and electric processes in the wearable thermoelectric generator. Equivalent thermal and electrical circuits of the facility should be as it is shown in figure 1.

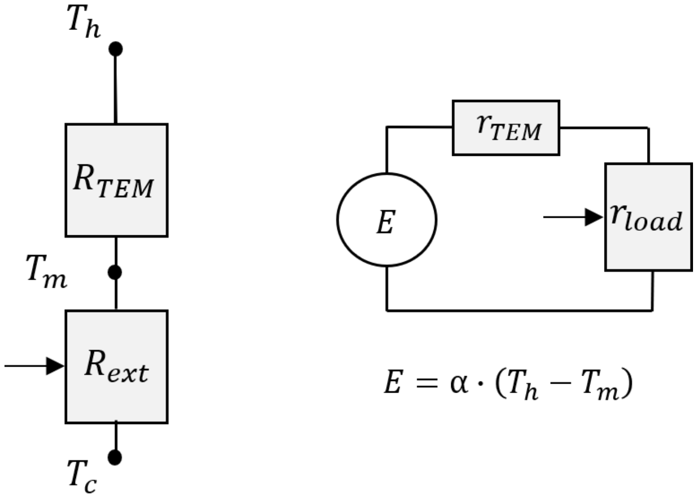


Figure 1: Equivalent thermal and electric circuits.

Two main parameters that should be easily adjusted during experiments are load resistance of the generator r_{load} and external thermal resistance of a thermal circuit of the generator R_{ext}. Such a facility will allow to validate theoretical model of WTEG and test DC-DC converter circuits.The facility should meet the technical requirements specified below to provide necessary accuracy for future experiments.

3 Technical requirements

The mechanical construction of the experimental facility should minimize heat losses through insulation and make heat capacitance lower. Temperature sensors should be SoC (system on chip) solution that has small size, digital interface, do not need external amplifiers and complex calibration procedures. The frequency of measurements should be no less than 5 Hz, accuracy should be as small as possible, but no worse than 0.15°C. Temperature control system should sustain predefined level of temperature within 0.1°C error. The maximum stabilized temperature difference in the facility should be no less than 12°C that corresponds to the temperature difference between human body and typical indoor conditions.

4 Design

4.1 Breakdown structure and the principle of operation

The designed experimental facility consists of a data acquisition system, a temperature control system and power generation system. The breakdown structure of the facility is represented in figure 2. The principal scheme of the facility is represented in figure 3.

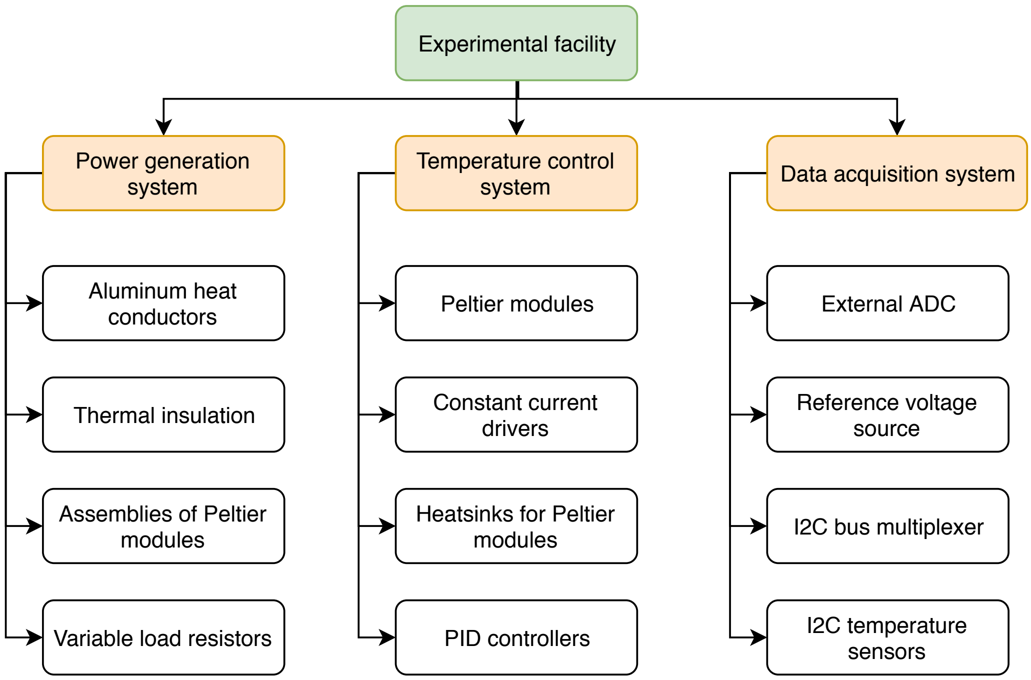


Figure 2: Breakdown structure of the experimental facility

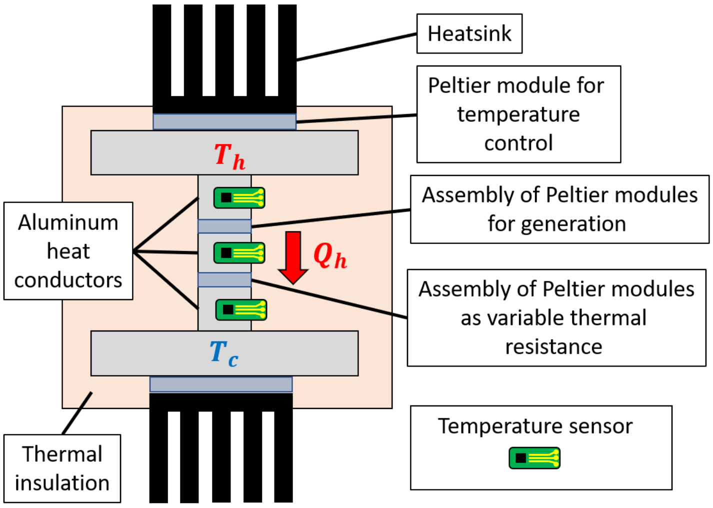


Figure 3: Scheme of the experimental facility.

Temperature control system provides a specified temperature difference between two identical aluminium details by stabilizing their temperatures (T_h and T_c) separately by PID controllers. Temperature sensors that are attached to the key components of the facility provide necessary input data for the controllers.

Because of the temperature difference in the system, a heat flux occurs and we can observe the distribution of temperature gradient among the parts of the thermal circuit.

The temperature differences across assemblies of Peltier modules causes an electromotive force in an appropriate electrical circuit. As two assemblies of small Peltier modules are connected to the load resistors, the voltage differences across the resistors and therefore power generation can be observed and measured by the data acquisition system. Mentioned two assemblies are physically identical, but their roles differ from each other. One of them is used for generation, the other plays a role of a variable thermal resistance and imitates different conditions of heat transfer that is not constant in a real system.

4.2 Power generation system

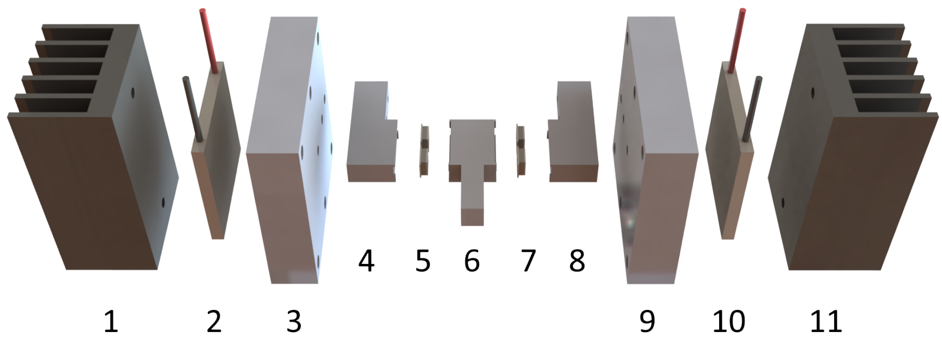


Figure 4: Exploded 3D view of the experimental facility, where *1* - top heatsink, *2* - top Peltier module for temperature control, *3* - top aluminum plate, *4* - aluminum heat conductor №1, *5* - assembly of Peltier modules as variable thermal resistance, *6* - aluminium heat conductor №2, *7* - assembly of Peltier modules for generation, *8* - aluminium heat conductor №3, *9* - bottom aluminium plate, *10* - bottom Peltier module for temperature control, *11* - bottom heatsink. The temperature sensors and thermal insulation are not included.

Mechanically the experimental facility consists of the details represented in figure 4. Aluminium plate *3* and conductor *4* has the same temperature T_h, stabilized by temperature controller. The details *8* and *9* also have equal temperature T_c, stabilized by another temperature controller.

Two assemblies of Peltier modules (the details *5* and *7*) and central aluminium heat conductor (the detail *6*) are connected thermally in series and form a thermal circuit with source of temperature difference $\Delta T = T_h - T_c$. The central heat conductor has high thermal conductivity ($\lambda_{AL} \approx 400W/(m \cdot K)$) that makes thermal resistance of this part negligible in comparison with the assemblies.

Moreover, to reduce contact thermal resistances in the system all contact surfaces are covered with thermal paste and two aluminium plates (the details *3* and *9*) are normally tied together with metric fasteners of size M4. In addition, to reduce heat losses and meet technical requirement all surfaces of the facility except heatsinks are covered with thermal insulation that is not represented in the figure 4.

As a result the whole temperature difference $T_h - T_c$ is distributed among two assemblies of Peltier modules (the details *5* and *7*). The assembly *7* is externally connected to the variable resistor, so generation in the electric circuit occurs. The power can be calculated from the measured voltage across the resistor. The assembly *5* is also connected to the variable resistor. If we know the value of this resistor then we can calculate effective thermal resistance of the module using parameters of thermoelectric modules in assembly.

4.3 Temperature control system

The temperature control system consists of two Peltier elements, two heatsinks, two constant current drivers and two PID controllers as it can be seen from the figure 2. The driver powers Peltier module TEC 12706 (the detail *2*) that creates heat flow from the aluminum plate (the detail *3*) to the heatsink (the deatail *1*) for hot side. For cold side the process is the same, but an orientation of the module (the detail *10*) is opposite and therefore the heat flux is reversed. The current driver is controlled by an analog signal from the DAC peripheral module of the STM32 microcontroller. To provide a necessary temperature within the specified range PID control is used that takes a measurement from an appropriate temperature sensor as an input.

Basing on the requirements a temperature sensor Si7051 from Silicon Labs has been chosen for measurements. It is factory calibrated, has a small 3x3 mm DFN package, a digital I2C interface. Its accuracy is 0.13°C in the range from 20°C to 70°C. A custom PCB was designed and manufactured for the sensor. It has a small size, contains necessary components for normal operation and thermally conductive pad for better thermal contact between the sensor and the target surface. In the figure 5 a photo of assembled temperature sensors can be found.

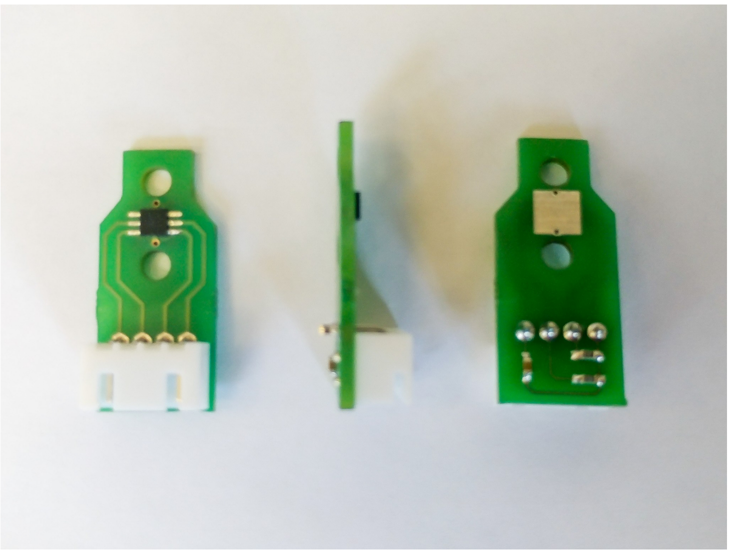


Figure 5: Assembled temperature sensors.

4.4 Data acquisition system

The data acquisition system contains external 16-bit low frequency ADC AD7705 with two fully differential inputs for measurements of a voltage across the load resistance. A combination of the ADC and an external voltage source AD441 ($V_{ref} = 2.5V$) provides accuracy better than 1 mv for the measurements. The STM32 microcontroller communicates with the ADC through the SPI interface.

As each temperature sensor SI7051 have fixed I2C address, the bus multiplexer PCA9548APW from NXP is used to access all the sensors. It allows to connect up to 8 sensors and to initiate different procedures (e.g. reading the data) synchronously for all the sensors.

5 First results

By the end of Industrial Immersion practice all mechanical components, PCBs for the control board and temperature sensors were designed and manufactured. The entire experimental facility was assembled and launched. Figure 6 is a photo of the main PCB that includes hardware of the data acquisition and temperature control systems. The electrical schemes of the PCB can be found in appendix. Figure 7 shows real assembled experimental facility.

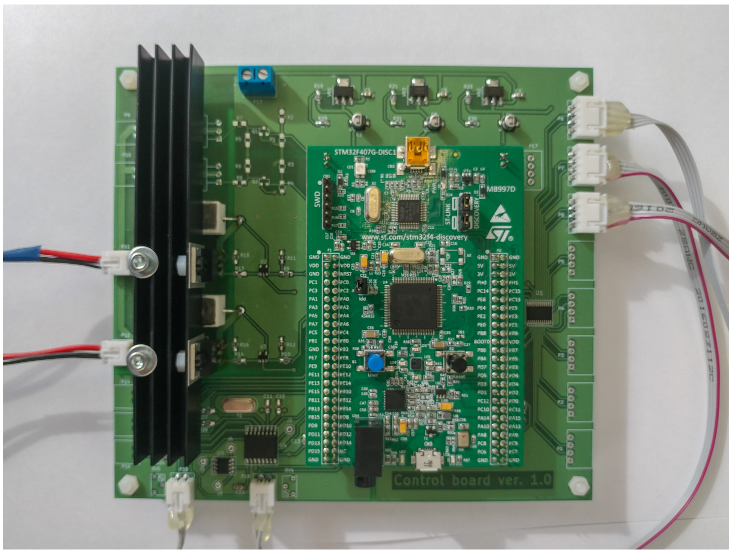


Figure 6: A photo of the control PCB.

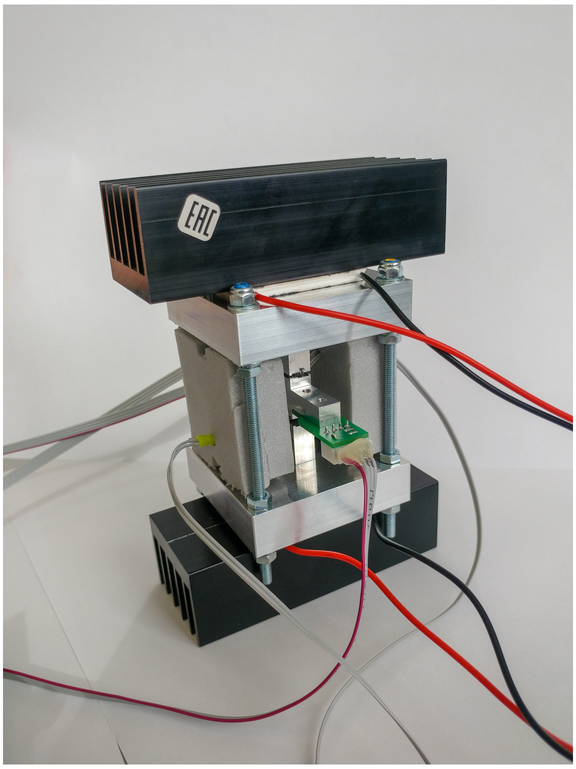


Figure 7: A photo of the experimental facility partially covered with thermal insulation.

During the first launches of the facility, some problems with insufficient heat dissipation from the current drivers were quickly revealed and solved. The other systems of the facility (see figure 2) were not changed and they work according to the expectations. The first rough tests of the temperature control system showed that the system meets the requirement of keeping the error of temperature stabilization within 0.1°C. The figure 8 proofs this statement representing a dependency of temperature T_h on time in milliseconds.

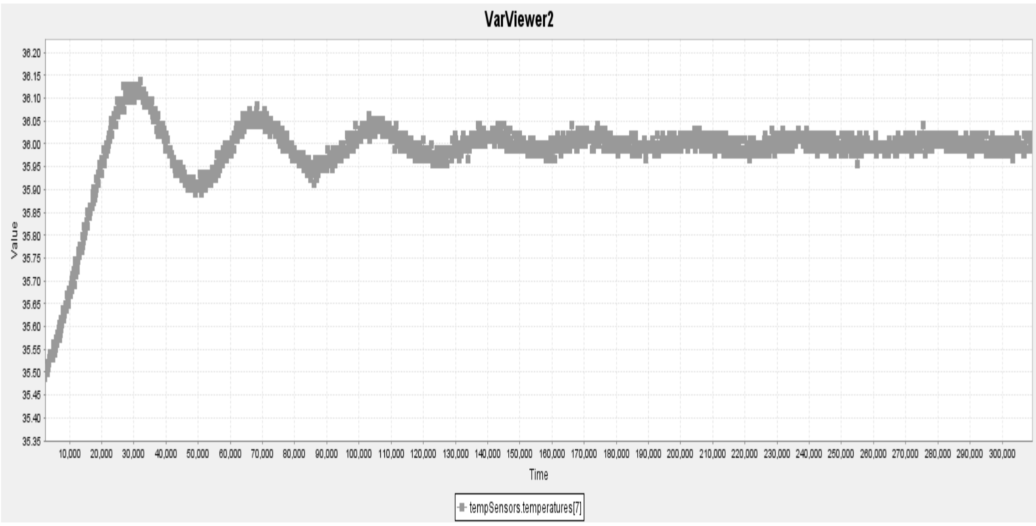
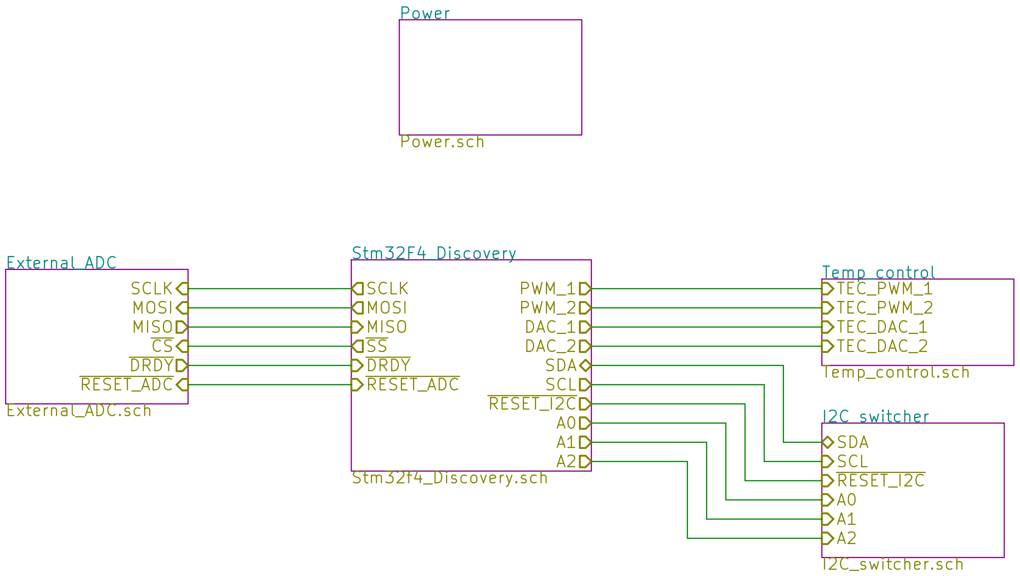


Figure 8: A screenshot from STMStudio of the dynamics of the top aluminium plate temperature control during first tests.

The value of the stabilized temperature T_h is 36.0°C that is 11°C more than typical indoor temperature. Basing on this data it seems that the system can easily meet the requirements on minimum temperature difference ($\Delta T_{min} \approx 12°C$) because target temperature for cold side controller of the same construction should be only $T_h = 36 - 12 = 24$ that it is very close to the typical indoor value.

6 Conclusion

For the two months of the Industrial Immersion practice an experimental facility that imitates heat exchange, thermoelectric and electric processes in the wearable thermoelectric generator has been designed, manufactured and assembled. Some technical requirements such as the minimum stabilized temperature difference and the acceptable error of the temperature control were verified. Other requirements connected predominantly with the data acquisition system will be tested in future work. Moreover, a graphical user interface for displaying the key measured parameters of the facility in real time is planned. Such software will make the process of operation more intuitive and convenient.

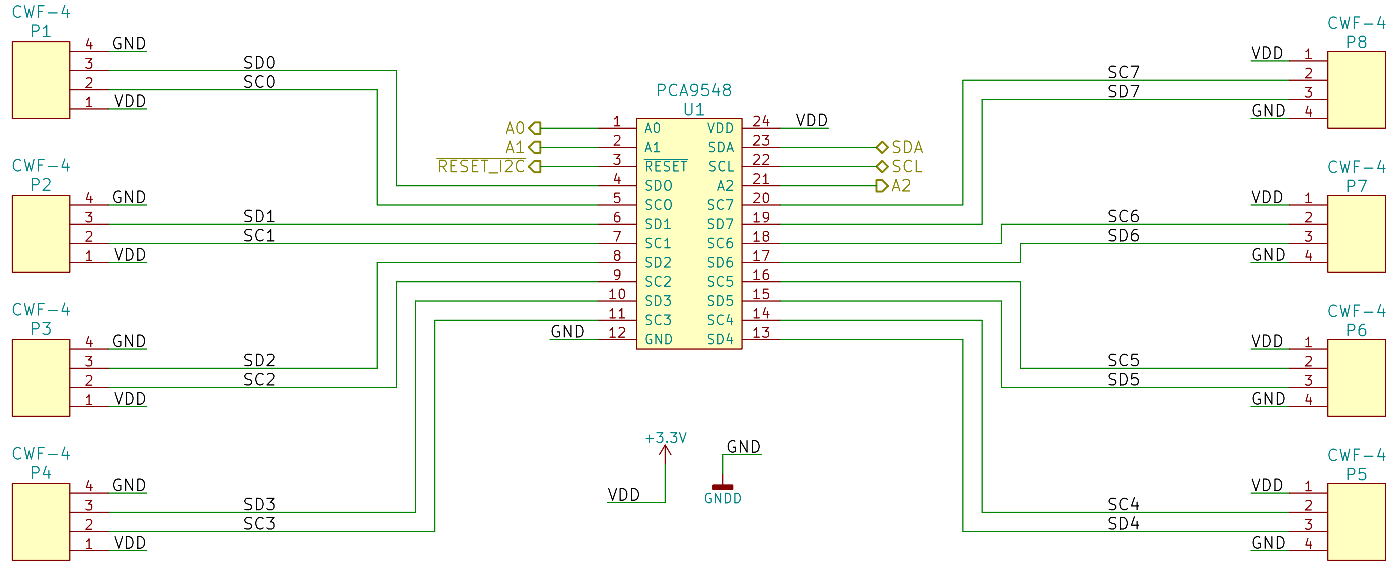


Skoltech

Sheet: /
File: Control board.sch

Title: Main sheet of Control board

Size: A4	Date: 2018-07-23	**Rev: 1.0**
KiCad E.D.A. eeschema 4.0.7		Id: 1/6



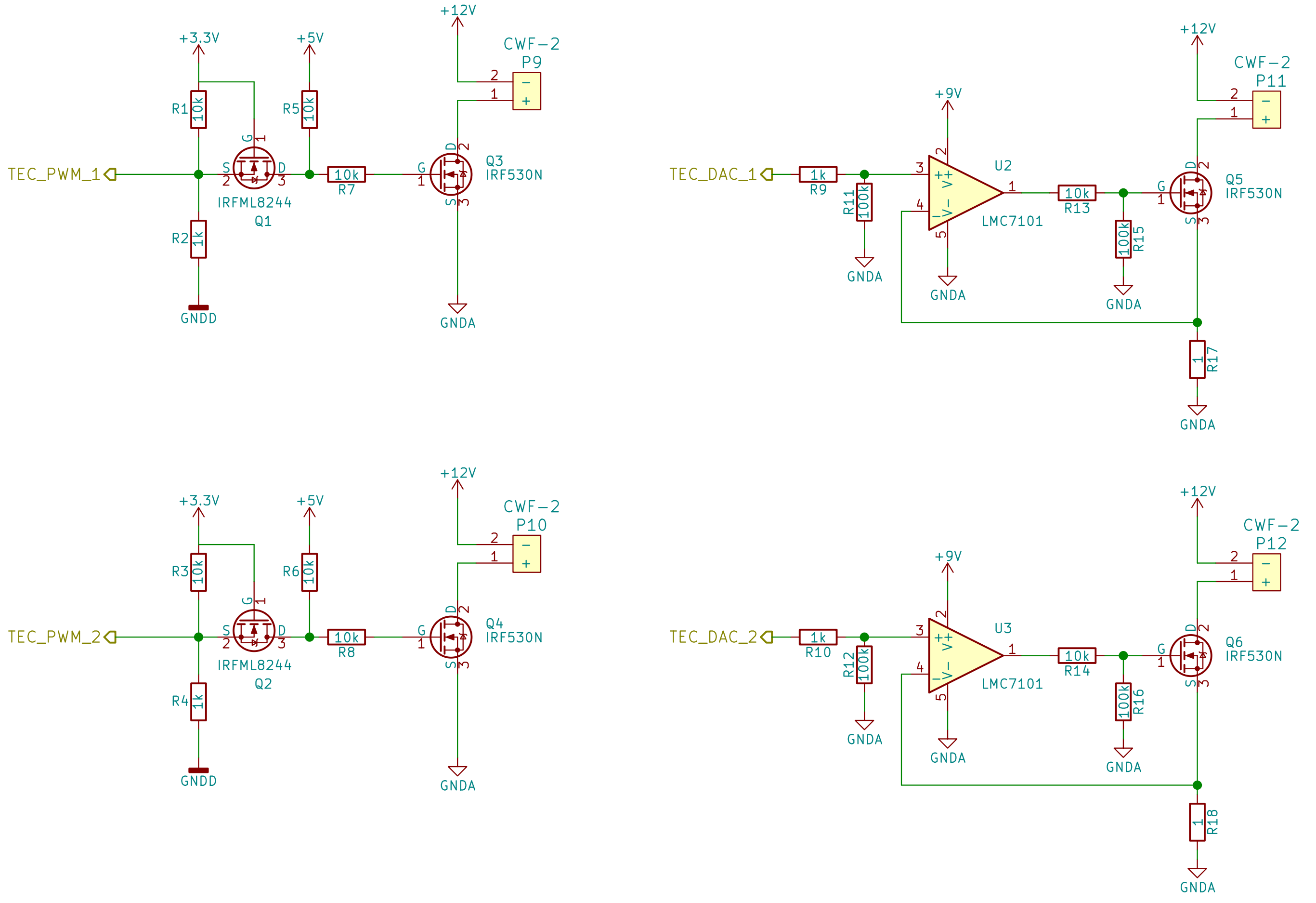
Skoltech

Sheet: /I2C switcher/

File: I2C_switcher.sch

Title: I2C multiplexer

Size: A4	Date: 2018-07-05	**Rev: 1.0**
KiCad E.D.A. eeschema 4.0.7		Id: 2/6



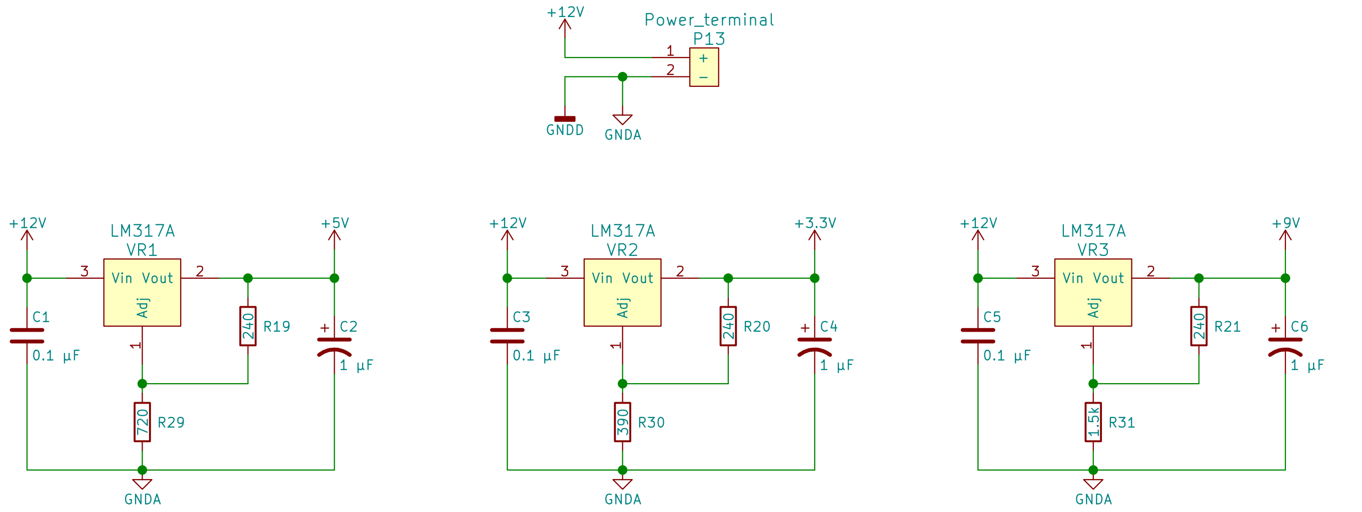
Left part powers ceramic resistors with PWM signal.
Right part drives Peltier coolers with constant current.
All together they provide temperature control.

Skoltech

Sheet: /Temp_control/
File: Temp_control.sch

Title: Current driver and PWM for temperature control

Size: A4	Date: 2018-07-05	**Rev: 1.0**
KiCad E.D.A. eeschema 4.0.7		Id: 3/6



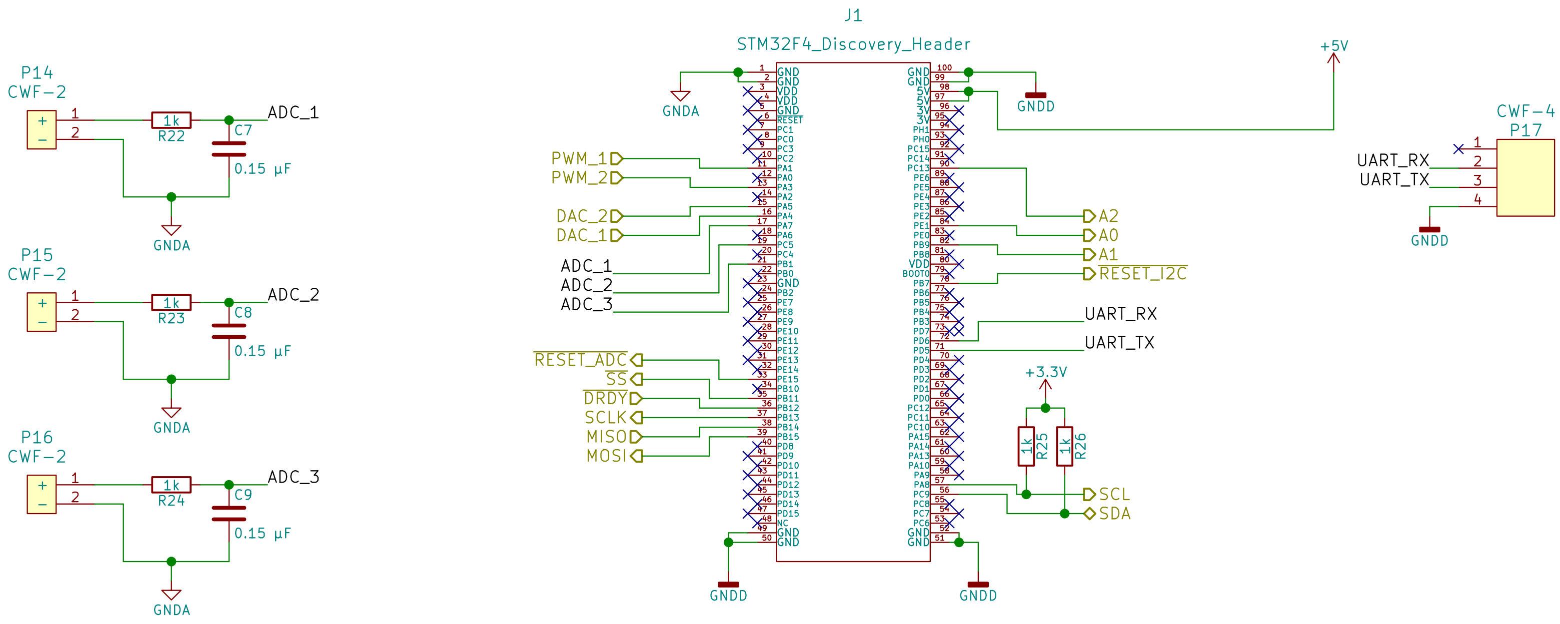
Skoltech

Sheet: /Power/
File: Power.sch

Title: Power supply

Size: A4 | Date: 2018-07-05 | **Rev: 1.0**

KiCad E.D.A. eeschema 4.0.7 | Id: 4/6



Skoltech

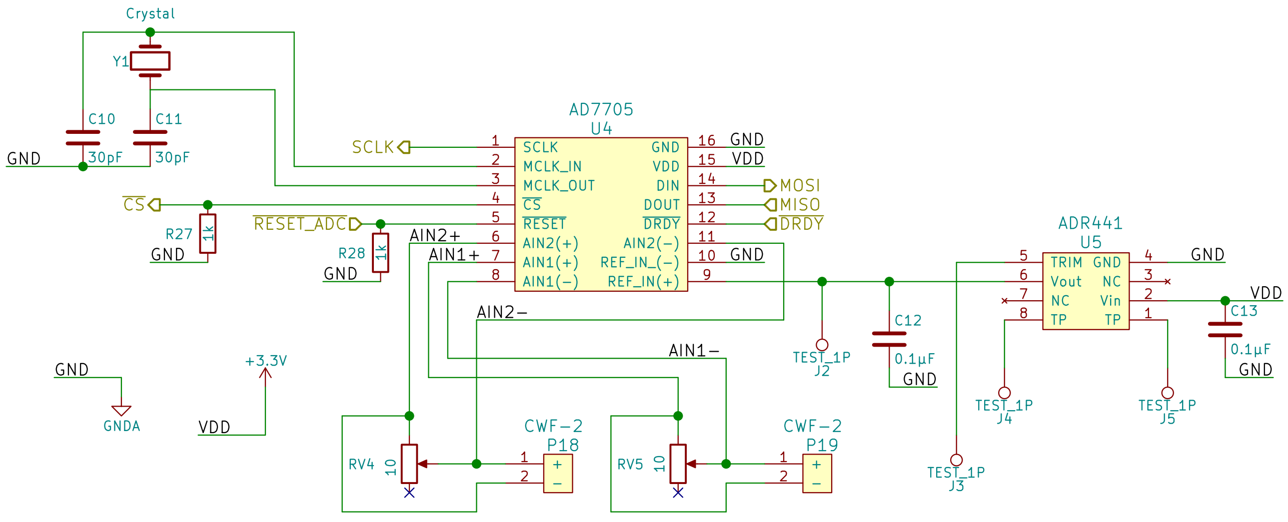
Sheet: /Stm32F4_Discovery/

File: Stm32f4_Discovery.sch

Title: MCU

Size: A4 Date: 2018-07-05 **Rev: 1.0**

KiCad E.D.A. eeschema 4.0.7 Id: 5/6



Skoltech

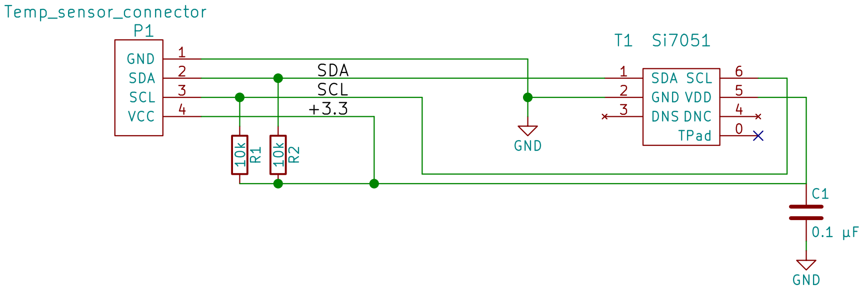
Sheet: /External_ADC/

File: External_ADC.sch

Title: External SPI ADC

Size: A4 | Date: 2018-07-05 | **Rev: 1.0**

KiCad E.D.A. eeschema 4.0.7 | Id: 6/6



Skoltech

Sheet: /

File: TempSensor.sch

Title: PCB for temperature sensor

Size: A4	Date: 2018-07-23	**Rev: 1.1**
KiCad E.D.A. eeschema 4.0.7		Id: 1/1