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MATLAB/Simulink Compatible Heater Lab Kit with USB Interface

Master thesis

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Declaration

Herewith I declare that this thesis is based on my own work. All ideas, major views and data from different sources by other authors are used only with a reference to the source. The thesis has not been submitted for any degree or examination in any other university.

Date:

Author: Signature:

Task of the thesis

Topic of the thesis:

MATLAB/Simulink Compatible Heater Lab Kit with USB Interface.

Termilise objekti katsemakett USB liidese ja MATLAB/Simulink draiveriga.

Initiator of the topic: Automatic Control and Systems Analysis Chair

Aims: To design a laboratory kit with interface to MATLAB environment

Expected results: Applied in practice project

Prerequisites: Refine the existing laboratory kit

Problems to be solved: Conception development, hardware and software design

Additional requirements:

Date: 04.02.2013

Student: Jevgeni Finajev	Signature:
Supervisor: Aleksei Tepljakov	Signature:
Approver:	Signature:

Abstract

The main task of this practical work was an attempt to simplify and to optimize some laboratory experiments students do during their studies of control theory. The work was mainly concentrated on developing a laboratory kit, which could provide basic functionality in learning, and modelling of control processes with necessary level of integration to computing and modelling environment like MATLAB. As a result, the laboratory kit should allow real-time data exchange between MATLAB's environment and object occurs during laboratory experiments, supporting all necessary control and data acquisition facilities.

The thesis is in English language and contains 79 pages of text, 8 chapters, 45 figures, 6 tables and 5 appendixes.

Annotatsioon

Selle praktilis-rakendusliku töö peamiseks ülesandeks oli laboratoorse katsemaketi väljaehitamine, mille abil saaks eksperemite kontrolli teoorias. Makett peaks tagada labori aja optimaalne kasutamine läbi integrerimine MATLAB/Simulink'i keskonnaga. Lihtsustatusd eksperementide käik ja maksiimallne kasutamine MATLABI/Simulink 'i koheselt ekperimentide jooksul tagab tedengitele häid võimalusi olla kontsentreeritud nimelt kontrolli teooria uurimiseks, rohkem kui rutini töö tegemiseks. Peamiselt, peab olema tagadud objekti omaduste õppimine ja analüüsimine ja kontrolli protsesse modelleerimine vajalikul tasemel. Lõputöö tulemusena on termilise objekti katsemaket mis võimaldab andmehõive ja andmevahetuse MATLAB keskkonnaga reaalajas. Töö eeldab riistvara disain ja tarkvara arendamine, ja nii nagu praktilise eksperimendi läbiviimine.

Lõputöö on kirjutatud inglise keeles ja sisaldab 79 lehekülge teksti, 8 peatükki, 45 joonist, 6 tabelit ja 5 lisa.

Glossary of abbreviations and terminology

°C	degrees Celsius
A	Ampere
actuator	a device controlling the flow of material or power
ADC	Analog-to-Digital Converter
API	**Application Programming Interface** Provide interface for communication software components in Windows environment
ASF	Atmel Software Framework
ATX	**Advanced Technology eXtended** a PC motherboard form factor specification
DAC	Digital-to-Analog Converter
DLL	**Dynamic Link Library** Implementation of the shared library concept by Microsoft
EEA	**European Economic Area**
embedded system	single-purpose small computer system dedicated for specific control functions
full speed	A term related to USB interface data transfer speeds not less 12 Mpbs
IC	integrated circuit
IDE	**Integrated Development Environment** Software environment for modelling and/or code engineering
IDP	integrated development platform
MATLAB	**MATRIX LABORATORY** A software environment provides technical computing and modelling for a wide range of technical systems. The trademark of MathWorks, Inc.
Mbps	**Megabits per second** data transfer rate
MCU	MicroController Unit
MIPS	million instructions per second
MOSFET	The metal–oxide–semiconductor field-effect transistor
PC	Personal Computer
PCB	printed circuit board
PSU	Power supply unit
Pt	Platinum
PWM	Power Width Modulation
Real-time	Circulated information about system is not outdated for time interval restricted by system behaviour

RISC	Reduced instruction set computing
rpm	Revolutions Per Minute
RS-232	Binary data transfer protocol
RTD	Resistance Temperature Detectors
sensor	a devices used to detect a change in a process with in some range.
Simulink	MATLAB tool for modelling and analyzing of dynamic systems.
TTL	**Transistor-Transistor Logic**
USB	**Universal Serial Bus** Communication protocol between personal computers and electronic devices
V	Volt
W	Watt

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1. INTRODUCTION

The studies, especially in technical disciplines, require student to spend significant part of learning time in laboratory to confirm theoretical knowledge by practical experiments. No doubt, the effectiveness of his work depends on personal qualities. However, enough equipped laboratory could essentially help student to avoid some routine work and save his time, allowing him to be more concentrated on main tasks such as analyzing or process modelling.

The experiments devoted to control theory suppose some object to be investigated, and some control algorithms to be realized in connection with its particular characteristics. The students usually start learning control theory on behaviour of thermal processes. The object for studying is a heating element embedded in a kit consisting of object itself, sensors and (or) actuators to make controls over various stages of experiment. An ideal laboratory kit minimizes the scope of routine work and provides the visibility of all processes with capability to change priority settings in real time. The kit must also enable real-time data exchange for closed-loop control applications and saving for further analysing and evaluating. The MATLAB [1] is a default computing and modelling environment used to deal with numerical computation and for modelling of dynamical systems in control theory discipline. Hence, we need some level of integration to MATLAB with capability of data exchange in real-time. The kit should provide some serial interface to PC, or rather USB interface as most accepted interface for personal computers.

The thesis begins with an overview of the kits commercially supplied to the market, followed by a description of existing kit belonging to chair's laboratory. Additionally, a few others kits examined for design and capabilities to meet our demands. The theoretical part describes the main conception of whole application. A block diagram will illustrate the structure of application. Data transmit protocol and time limitations will be discussed as well. The design chapter focused on kit's schematic and hardware design. The special section dedicates to IDE used for design, coding and testing of application. The testing part refers to practical application of the kit. Those procedures as object identification and controller modelling conducted to confirm declared capabilities. The whole work will be analyzed at the final part of the thesis.

2. OVERVIEW

2.1 Commercially available kits

2.1.1. Main features

The market of commercially available teaching kits is big enough to cover all scholar needs. The commercial kits provide extended support for studying and modelling of various processes, but purchasing of commercial kits sometimes quite expensive and may be limited by a budget. Furthermore, the commercial kits may sometimes require calibration and maintenance service bringing additional expenses and disturbances in laboratory activity. A brief survey given here to inform about educational capabilities of commercially available kits.

2.1.2 Temperature Control System from Cytron Technologies

The kit supplied by Cytron Technologies Sdn. The description of circuit found on company's web page [2]. This is microcontroller-based kit equipped with temperature sensor capable to measure ambient in range 0 - 100 °C and send the value on LCD display.
The kit also includes two fans and may be purchased for reasonable price around 40 US dollars with no delivery included. The microcontroller is PIC16F876A with 10-bit ADC

supplied by Microchip Technology Inc [3]. The Usage of kit is limited due to small amount of flash memory and supported interfaces. The kit supplied with open source code making it more flexible in context of embedding to high-level systems. No actuating devices for control attached on the board. The Figure 1 illustrates the mentioned kit.

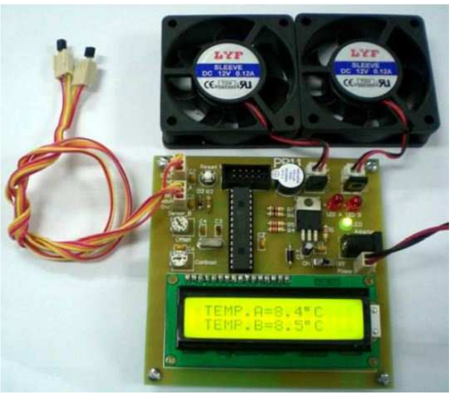

Figure 1.Temperarure control kit from Cytron Technologies.

2.1.3 Serial Temperature Sensor Interface Kit VK011K from QKits

Serial Temperature Sensor Interface Kit VK011K allows serial interface between up to 4 temperature sensors and PC [4], The measured ambient temperature range defined by temperature sensor Dallas DS18S20 [5] between -55°C to +125°C with 9-bit resolution. RS-232 interface serves to transmit data to PC and supply the board. The sample rating provided from 1 second to 99 minutes. The kit supplied with free software, but source code is not included. It causes the problem of compatibility with customer's specific needs. Furthermore, additional RS232 to USB Converter [6] required to support USB connectivity, because usual PC has no serial port in most cases. As in previous case, no actuating circuits included. The Figure 2 illustrates temperature kit VK011K.

Figure 2.Serial Temperature Sensor Interface Kit VK011K.

2.1.4 Temperature transducer and control kit from Elettronica

The complex educational kit from Elettronica [7] promoted as a powerful educational tool supporting various experiments involved in temperature processes control. The design accomplished regarding the industrial standards. The kit consists of board G34/EV and external unit TY34/EV. The board include 10 functional blocks which outputs and inputs are accessible for measurements with standard measurement tools. Experiments may include analyzing of temperature transducers and related conditioning circuits. The kit also provides automatic control with PID controller included. The blocks support interface to Pt-100 industrial temperature sensors [8], NTC and PTC type thermo resistance [9] and J-type thermocouple [10]. The kit includes low-voltage with triac phase control for supply of 100W heating element and power amplifier to supply cooling fan.

Figure 3 illustrates the educational board G34/EV with external unit TY34/EV from Elettronica.

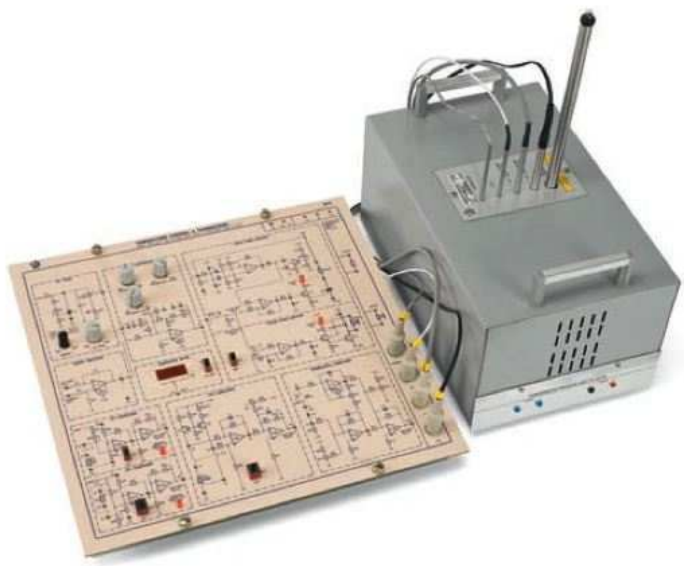

Figure 3.Educational board G34/EV with external unit TY34/EV.

The kit needs external power supply unit PS1-PSU/EV [11], which should be purchased separately. Figure 4 illustrates power supply unit PS1-PSU/EV.

Figure 4.Power supply unit PS1-PSU/EV.

Elettronica optionally offers USB industrial interface module MFI-U/EV [11] performing the data acquisition and exchange with PC. It carries out 12-bit resolution ADC and 8-bit resolution DAC. The module also supports 8 digital TTL inputs/outputs providing great capability for experimental work. Figure 5 shows the interface module MFI-U/EV.

Figure 5.USB interface module MFI-U/EV.

The module accompanied with USB driver, microcontroller firmware, DLL with API components compatible with Lab View software for interface software development.
Although the cost is not listed on manufacture’s site, we can courageously talk about, at least, few thousands euro. Fine solution for great money.

2.2 Custom designed educational kits

2.2.1 Main features

Custom designed educational kits, obviously, have some considerable advantages upon commercial. Custom design meets the specific needs of educational institutes. It usually low-cost and can be revised easily, adjusting to new specifications or demands for future experiments. Further, the designer group obtains invaluable hand-on experience and may even claim for patents in case of entirely new decision. Even some limited edition may be produced for distribution between other educational units. However, related work must be observed by qualified person and some tests may be required in compliance with existing standards in particular area.

2.2.2 The existing kit

The existing kit is taken first for consideration. The Figure 6 illustrates the kit used for base experiments in control theory on chair of Automatic Control and Systems Analysis of Tallinn University of Technology. It consists of heating element, cooling fan and a thermocouple as a temperature sensor. The power supply unit plugged in separately and shown on the left from kit.

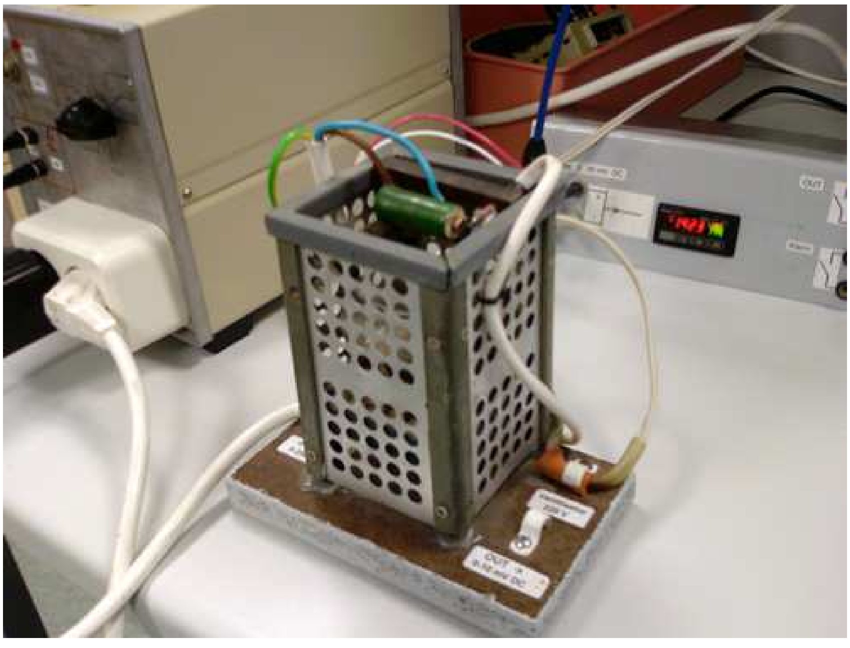

Figure 6.Existing thermo object with supply unit for laboratory work.

Many generations of students have used this kit for experiments and laboratory work during their studies. Regardless its outmoded design belonging to last century the kit is still good enough for many educational experiments and used extensively by students. However, on demand for more productive work focused on the main task the kit has some drawbacks. In order to perform all necessary operations the student has to switch between few modes, to fix some modes on oscilloscope and write down the results for further computing and calculations on personal computer with appropriate software (MATLAB) installed. Most of the operations to be done manually. It causes the time wasting. Furthermore, a high voltage in maximum of 220V AC is used to supply heating element. It raises the risk of electric shock during the experiments. Hence, in order to overcome the most of manual work and examine system behaviour on more visible way, a low-voltage and easy manipulated laboratory kit with extended capabilities becomes a reasonable decision.

2.2.3 Temperature control kit from Near East University.

The temperature control kit was created by D.Ibrahim from Near East University [12] placed in Lefkosa, Turkey. He described prerequisites and construction in his article in International Journal of Electrical Engineering Education [13] .The main motivation merely was a building a low-cost educational kit caused by a reason of conducting intended practical experiments for students. The kit's construction in pretty simple. Some criticism may be applied, but we‘ll not focus it. Anyway, on the assumption of released article, the kit performs and supports all necessary laboratory experiments for temperature control. The block schematic of temperature control kit represented on Figure 7.

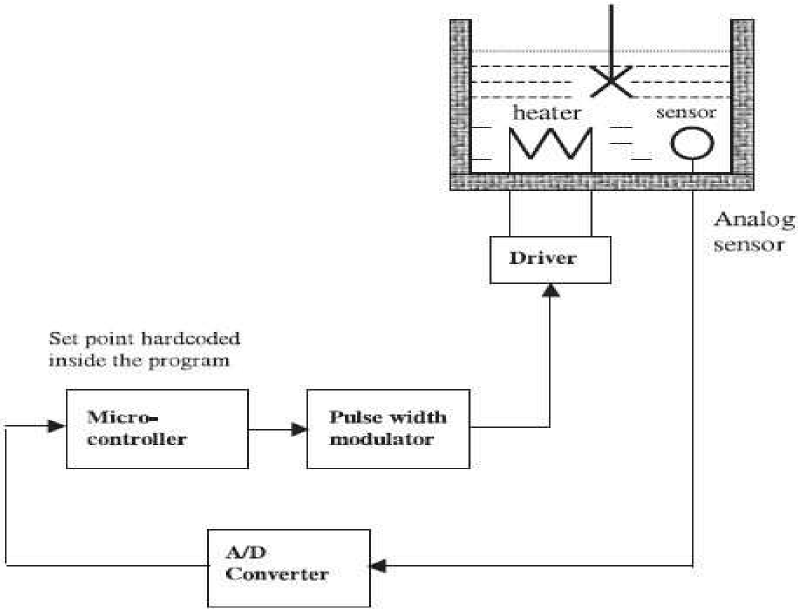

Figure 7. Schematic of temperature control kit from Near East University.

The main part includes a 12Volts/120W heater warming the water in a plastic container. The temperature of ambient water measured by a temperature sensor LM35DZ [14]. The microcontroller PIC16F877 [15] from Microchip drives the MOSFET switch IRL1004 [16] with PWM impulses dosing the portion of energy directed to the heater. The circuit diagram shown on Figure 8.

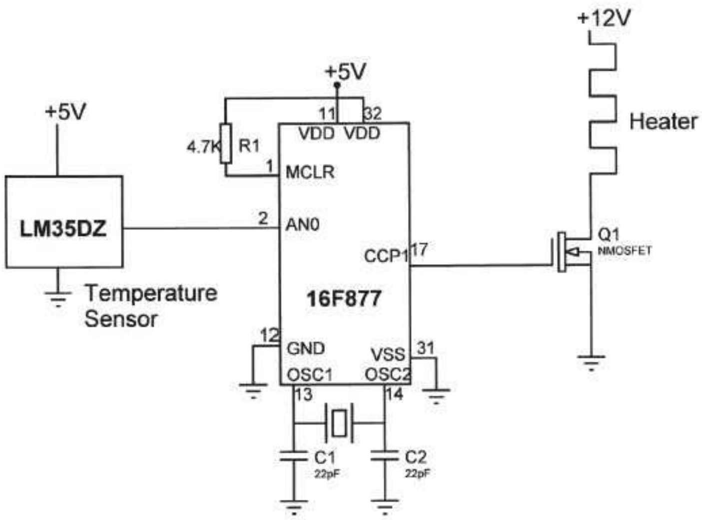

Figure 8.Circuit diagram of temperature control kit from Near East University.

The kit constructed on the stand like shown on Figure 9.

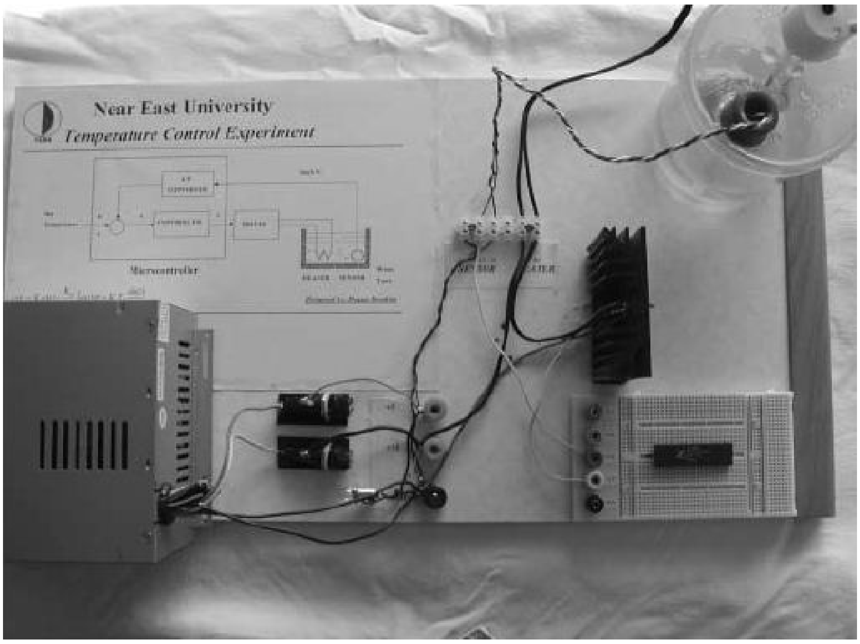

Figure 9.Temperature control kit from Near East University.

As seen from figures above no data transmission provided to PC. The price declared with in 200 US dollars is moderate or even high for this class of systems.

2.2.4 Education temperature control kit from Slovak University of Technology.

The advanced educational and trainer temperature plant was built in Slovak University of Technology in Bratislava [17]. More than 40 similar kits are successfully used in labs of several EU universities. We have no detailed schematic provided, but can refer to few articles [18] [19]. Figure 10 illustrates the thermal educational plant from Slovak University of Technology. The kit equipped with 20W halogen bulb as a heating element,

Figure 10.Thermal educational plant from Slovak University of Technology.

temperature sensor Pt-100 and low-voltage fan for control and imitation of disturbances. The 12-bit resolution converter provides precision less than 1%. Electronic subsystem contains all necessary components to acquire data from sensors, control plant's actuators and communicate with PC through USB interface. The data include plant temperature, ambient temperature, bulb light intensity, fan speed (only informative) and fan current. The plant can be controlled through either analog or USB interface. USB connectivity is provided by USB converter. Data can be transmitted to MATLAB/Simulink where the plant is represented as a single block. A similar solution is also available for open-source environment Scilab/Scicos. The spaces of experiments are extended through capabilities of kit provided by more than a 20 year long of development work. Probably, that is one of the best educational kit. In case you want to purchase it, you will pay nearly 5000 euro.

3 HEATER LAB KIT PRELIMINARY DESIGN

3.1 Conceptual design

3.1.1 Object

Regarding the previous chapters, the temperature control processes are most preferable for initial experiments in control theory. Students forced to use simple physical thermo objects to observe initial conditions, object states and dynamic behaviour of entire system. They can realize clear control algorithms implementing basing well known evaluating methods to design a feedback control.

The object for temperature control may be either gas, liquid or solid object. The gas and liquid require additional design to isolate from ambient. Some vessels or tubes must be added to kit's construction to store them. Complementary design complicates the scope of work and increases the cost of the project. In safety aspects, vessel may occasionally be damaged or ever broken during the laboratory experiments because of human mistakes.

It raises the risk of injuries. Thinking so, we leave the consideration of gas and liquid and staying focused on solid objects.

The temperature control of a solid object performed in simpler way – no needs any vessels, but only solid object itself and temperature measuring device, attached to it. Usually, the role of solid object plays a heating element. The same conception of object is realized in existing laboratory kit described in Section 2.2.2 . We will follow the same way and take a heating element as an experiment object for implementing in next generation kit.

3.1.2 Functionality: the formula of "four E"

The discuss about functionality of experimental tool have already been touched earlier.

Here we can summarize the scope of functionality targeted to simplifying the workflow and allowing an experimenter to implement necessary analyzing and modelling tools with minimum efforts applied. The derived formula of functionality can be released in view of "four E": easy manipulation, easy analyzing, easy modelling and easy modernization.

- **Easy manipulation** refers to shortening the time of switchover procedures with no loss the quality of experiment workflow. In others words, all main and auxiliary controls to be performed on computer-based principle: one-two mouse click with minimum efforts and distraction from main process supervising.

- **Easy analyzing** refers to capabilities to use powerful and easy manipulated analyzing and computing tools delivered by computer-based platforms like MATLAB, LabVIEW [20]etc.

- **Easy system modelling and simulation** overlaps with previous item and refers more to powerful and easy configurable modelling tools, allowing the individual approach to experiments. The system may be represented like a synthesis of physically real object with its natural behaviour and various virtual objects or processes in connection with particular needs of an experiment.

- **Easy modernization** refers to minimizing costs and efforts for future modernization through the easy integration of a required module to an existing design. The system has to be able to serve updated controls and data acquisition with in some limits. The developer has to compromise between the cost of the project and establishing the design in perspective of future modernization.

With this formula, the design will span all existing and future demands within some scope for years.

3.1.3 Safety compliance

One of most important aspects of engineering design is following the human safety requirements. If electrical equipment intended to use in EAA countries, the EU directives relating to electrical equipment designed for use within certain voltage limits must be followed [21]. The mentioned directive based on The Electrical Equipment (Safety) Regulations 1994 (S.I. 1994/3260) [22] classifying electrical equipment into two groups:

I. Equipment intended to use voltage between 50 and 1000 volts in the case of alternating current
II. Equipment intended to use voltage between 75 and 1500 volts in the case of direct current

The directive prescribes the CE marking for all mentioned equipment, circulated in EAA countries. It declares that only electrical equipment, which does not endanger the safety of people, domestic animals and property, shall be placed on the market.
Besides the EU directives some international standards like IEC 60601-1 [23] prepared and saved by International Electrotechnical Commission [24] have to be taken into account.
Anyway, the common approach in electrical design based on minimizing of electrical shock hazard. Less voltage causes less current in main. Hence, engineering sight towards a low-voltage solution is fully acquitted. Low voltage is a relative term. In our case, the upper limits of voltage determined in context of electrical hazard. Regarding the articles devoted to electrical shock effects [25] [26], the maximum current occurs upon a contact of any electrical source with a human body part must not exceed so called "let go threshold" level 10-20 mA, when "cannot let go!" state occurs. The resistance of human body varies from100 000 Ohm on dry skin to 1000 Ohm on wet. Therefore, using Ohm's law, we can calculate the maximum safe voltage

Equation 3-1

$$U_{max} = 15mA \bullet 1000\ \Omega = 15\ V.$$

Hence, the level near 10-12 volts in the case of direct current would be fully acceptable.
The maximum voltage in the case of alternate current is cut down due to property of human skin, which acts as a capacitor making total resistance much lower.
All interested persons may be addressed to comparison of safety criteria given by the American IEEE Std 80-2000 and European IEC 60479-2005 Standards [27].
Anyway, the proper design should include the parts already have obtained at least CE marking.

3.2 Functional design

3.2.1 Main structure of computer-based experiment system

Computer-based experiments require a personal computer and a peripheral control system. Personal computer offers great computing, analyzing and modelling capabilities, supported by MATLAB in our case, and peripheral control system performs all routine operations in experiment. Data exchange provides from each side. Main control driven by PC and local control performed by a peripheral control system. The structure shown in Figure 11.

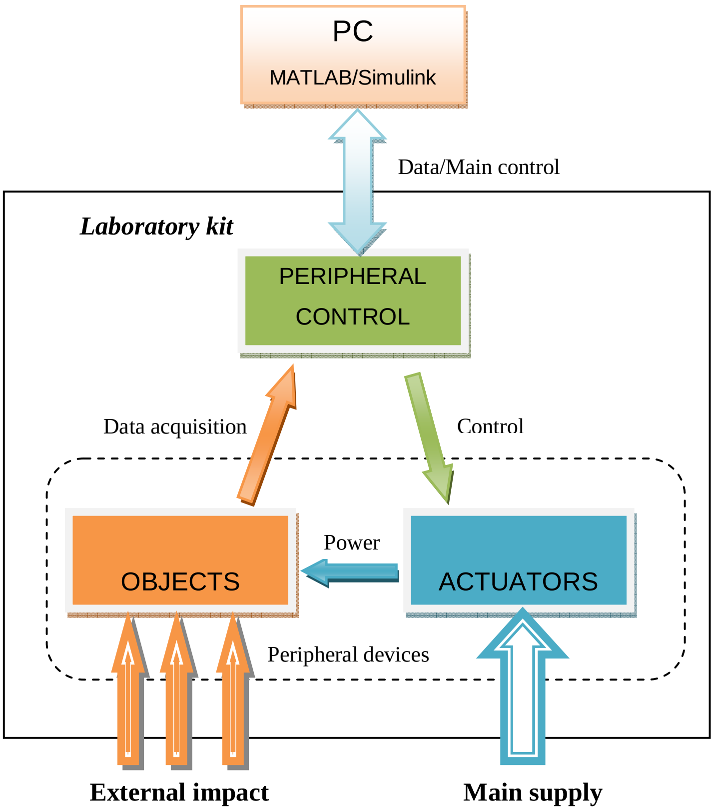

Figure 11.The typical structure of computer-based experiment.

The amount of peripheral devices and controls varies from the type and scope of experiments. Peripheral control usually is a microcontroller-based solution. Modern microcontrollers due to extended capabilities offer great opportunities for resolving custom design, providing enough computing support and operational speed to control systems in real time. The ratio between cost and performance pushed microcontrollers widely used beginning from toys and finishing the complex systems in all technical spheres.

3.2.2 Heater Lab Kit's functional design in context of temperature control

No changes detected from PC side. We only need to specify peripheral devices to meet particular requirements of experiment. The Figure 12 represents the block diagram of the kit with its specific design adapted to scope of experiments for temperature control.

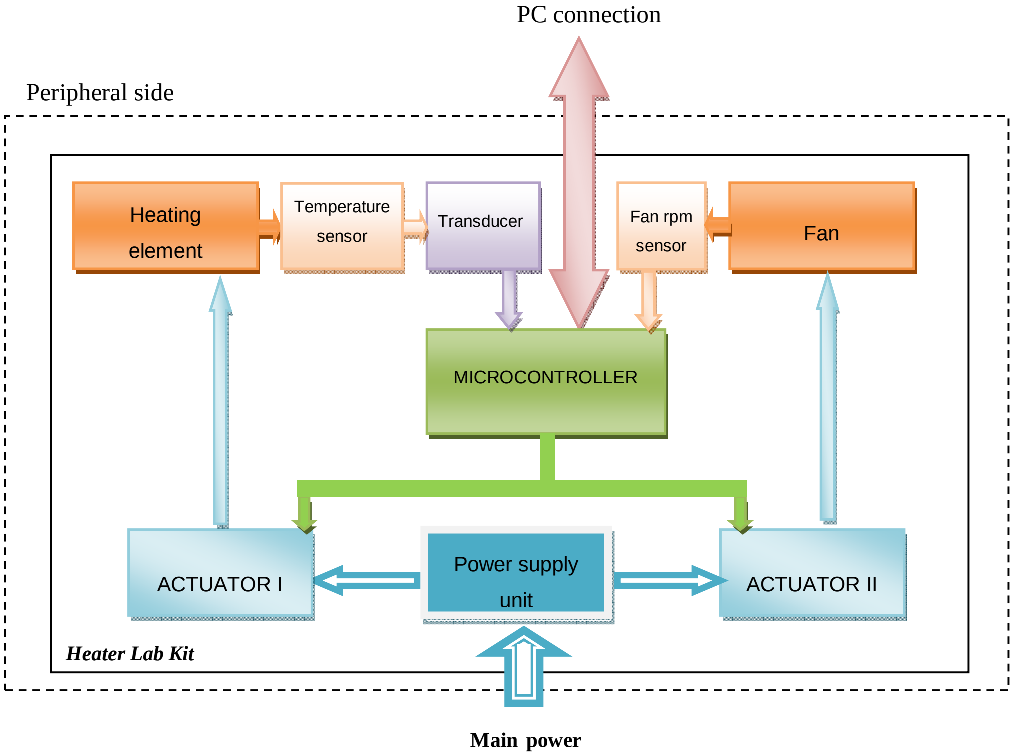

Figure 12.Heater Lab Kit's functional block diagram

Functional description of each element explained in Table 1.

Table 1.Functional units of computer-based temperature control experiment.

Unit	Amount	Functional description
	PC side	
PC with MATLAB environment installed	1	Main control and data analyzing; data exchange
	Peripheral side	
Microcontroller	1	Local control; ADC conversion and data handling; data exchange

Heating element	1	Base object for experiment
Temperature sensor	1	Temperature measuring device
Transducer	1	Temperature sensor's signal conditioning
Auxiliary fan	1	Cooling and producing disturbances
Fan’s rpm sensor	1	Fan’s rpm measuring device
Actuators	2	Power drive for fan and heating element
Power supply unit	1	Low-voltage supply

Upon this functional description we can form a scope of requirements or a list of essential technical statements that span methods, processes or services that enable a system functioning. The scope of requirements represented in form of technical specification for each functional unit implemented in the design. Specification gives real approach to measure the conformance of any circuit or platform.

The specifications will be prepared abiding the kit’s design conception elaborated in Section 3.1 and functional design presented in this section.

3.3 Design specification

System design specification

The system design proceeds from number of statements:

- Ensure a possible minimal effect to PC peripheral due to electrical isolation of hardware component intended to use in design;
- Nominal voltage used in system must not exceed the voltage rating derived in Section 3.1.3 for human safety compliance;
- The access to electronic components or open contacts during practical exploitation to be minimized ;
- The possibility of visual observation for components to be provided in educational purposes;
- Components intended to use must comply the EU directives or standards;
- To be compact with friendly design;

Microcontroller

A microcontroller is a small integrated circuit containing a processor core, data storage memory, and peripheral interfaces. More powerful MCU can additionally include modules for ADC and DAC conversions, USB interface, and PWM control.

Microcontroller device is a heart of our lab kit that manages the power and data stream in real-time. Hence, we need a MCU that:

- Supporting full-speed USB 2.0 interface with USB CDC library support(will be explained later in chapter dedicated to software development) ;
- Supporting real-time performance with fast interrupts handling comparing with the controlled process time stream;
- Include at least few ADC inputs to provide existing and future demands;
- Include a few PWM channels with different modes of control;
- Provides enough SRAM and flash memory for data and program storage for now and in perspective of future modernizations;
- Having a good developed IDE platform with extended third party developers;

Heating element

No special requirements derived for heating elements. Regarding the temperature range of experiments provided by existing kit, we inspired to define the same range. Hence, the heating element:

- Allows temperature control experiments in range from 0 °C to 250 °C;
- Emits enough heat on low voltage supply to provide required temperature range;
- Has enough amount of working hours to serve experiments for years;

Temperature sensor

Temperature sensor specification:

- Provides robust measurements in required temperature diapason;
- Has a minimum possible non-linearity in characteristics with predictable behaviour;
- Compact and easy integrated;

Transducer

Transducer's specification depends on characteristics of temperature sensor. Anyway, the transducer must be

- Compact;
- Easy adopting to some range of input and output signals;

Auxiliary fan

Fan specification includes the next requirements

- Compact;
- Low-voltage supply;
- Embedded rpm sensor;

Actuators

Actuators distribute power for supplying units in the system. In most of low-voltage applications PWM control used to deliver portions of energy to consumer.

The control realized in easy way due to interfacing with PWM modules embedded to MCU. Hence, actuators should:

- Support PWM control from MCU controlled interface ;
- Ensure power output within operational voltage;
- Provide reduced power loses on switching;
- Provide heat dissipation on required current;

Power supply unit

Power supply unit converts main power AC voltage to required DC low-voltage in our case. The requirements to PSU flow from various restrictions applied to output voltage and current. They are usually common and include:

- Rated voltage and power;
- short circuit protection;
- overload and overvoltage protection;
- over temperature protection;
- budget solution
- CE marking due to requirement for appliances with AC voltage exceeded 50 Volts.

3.4 Component selection

3.4.1 Microcontroller

Regarding the microcontroller's specification in the Section 3.3, we need a general-purpose MCU with embedded ADC converter, USB stack and PWM control's capabilities. AT90USB1286 microcontroller [28] of megaAVR family from Atmel Corporation [29] seems reasonable candidate for our purposes. It provides all necessary capabilities and accompanied by IDE platform supplied by manufacturer, and by third party of developers like Source Forge team with their open development suite WinAVR™ [30].

AT90USB1286 produced in TQFP64 or 64-lead QFN packages with quite tiny pin design and a gap between pins only 0.3 – 0.5 mm. It complicates soldering operations. For this reason, the **Teensy++ USB Development Board** of version 2.0 [31] with the already embedded AT90USB1286 microcontroller became the final solution. It has a standard pinout with gap of 2.54 mm preferable for preliminary hardware design using breadboard [32]. Figure 13 illustrates the Teensy++ top view.

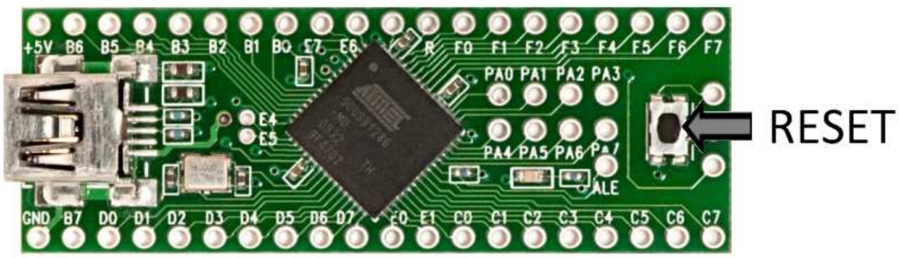

Figure 13.Teensy ++ 2.0 USB Development board.

Teensy++ is a complete USB-based microcontroller development system with good developed "how-to" tips. The new board supplied with HalfKay bootloader. HalfKay, together with the Teensy Loader software, allows convenient and fast way to reprogram the microcontroller with only one press of Teensy++ RESET pushbutton. The board powered from USB. It gives a capability to connect a low-power sensor without external supply.

3.4.2 Heating element

Heating element that utilizes the main AC power is easy accessible. However, for low-voltage design we need a particular solution.

D.Ibrahim in his construction [13] used a low-voltage heater that is not compact and designed for water warming. We inspired to use a hand-made heating element from the beginning. The material intended to use was a Heating Wire Nickel-Chromium Alloy [33]. Although hand-made heater emitted enough heat, we had no way to attach a sensor to it. It violated the conditions of experiment. We measured a temperature of ambient instead of a temperature of the heating element. We could not also guarantee enduring life cycle.

Another solution refers to powerful resistors with working temperature range nearly required diapason. Online catalogues offer a variety of types, but inspiring the lifetime of existing laboratory kit we founded wirewound resistors satisfy our specification. Finally, a axial wirewound resistor of model G206 and rated characteristics 2.2 Ohm/13W chosen from Vishay Draloric [34]. The resistor's temperature curve depicted on Figure 14.

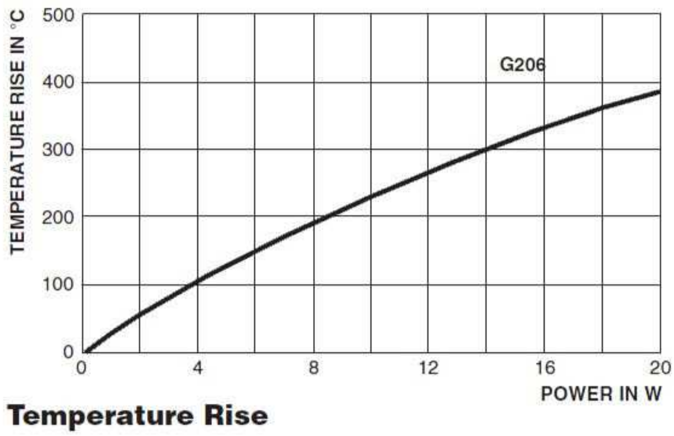

Figure 14. The curve of temperature rise for G206 model resistors.

Resistor can work on temperatures nearly 300°C on its peak dissipation power. We need to calculate a supply voltage on peak power in order to get understanding about voltages delivered to the kit. Manipulating a formula for the dissipated power as function of voltage and resistance, we obtained the necessary value:

Equation 3-2

$$P = \frac{U^2}{R},$$

and, transforming this Equitation 3-2, supply voltage founded

Equation 3-3

$$U = \sqrt{P \bullet R} = \sqrt{13W \bullet 2.2\Omega} \approx 5.3V.$$

3.4.3 Temperature sensor

Due to requirement for minimal possible non-linearity, only Platinum RTD considered as satisfied. They provide stable rise around 0,385Ω/°C (Pt100 RTD) for temperatures above 0°C. The small non-linearity compensated by appropriate calculations. Maximum detected temperature limited by constructive features and not exceed 500°C.

Market offers a wide range of industrial and integrated RTD classified in accordance with a typical resistance at 0 °C. Pt100 RTD has a typical resistance 100 Ohm and Pt1000 has 1000 Ohm accordingly.

Integrated RTD offer compact design and embedding capabilities. They consist of thin ceramic film and platinum resistor. A similar Pt100 sensor from JUMO [35] selected for our design. Figure 15 illustrates the design and dimensions of the sensor.

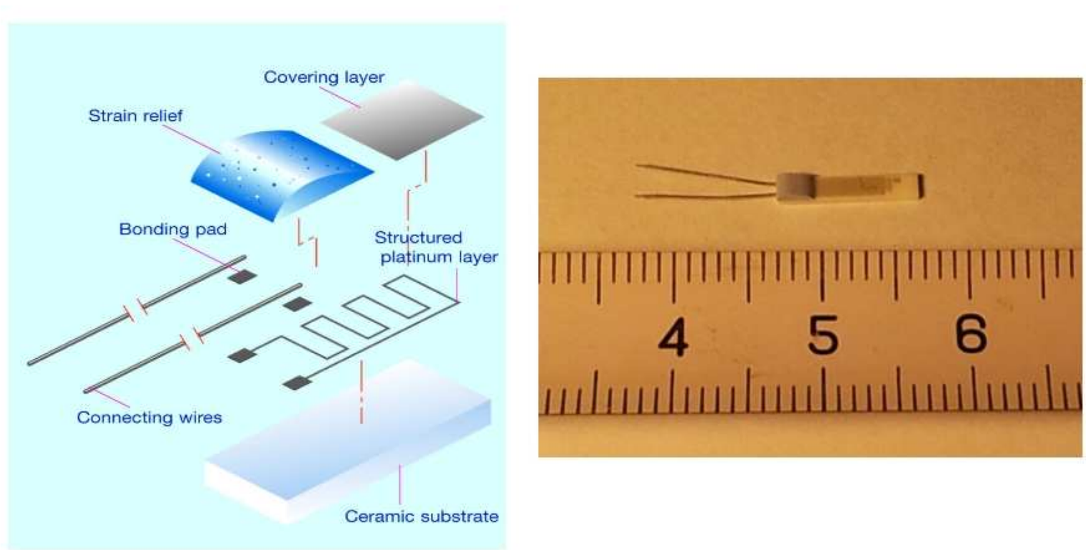

Figure 15.Pt100 temperature sensor from JUMO.

Measuring current passed through sensor is limited by 7 mA due to self-heating effect.

3.4.4 Transducer

We did not suppose to use some single device. Industrial transducers are expensive for our project initially. A custom design implemented for this unit as most suitable solution. All transducer's design aspects discussed in a section dedicated to schematic development.

3.4.5 Actuators

MOSFET switches used as power drives in billions of appliances. They are most suitable devices for embedded systems with DC control. Microcontroller manages the portions of energy with PWM control not directly but over control of MOSFET switches. Other types of transistors may be used too, but MOSFET constructively has electrical isolation of control side from power side. Moreover, they provide clear switching characteristic.

A MOSFET switch controlled by a potential applied to the Gate input, opening or closing Drain-to-Source power stream. N-channel MOSFET switches with Drain-to-Source Voltage V_{DSS} nearly 30 Volts and Continuous Drain Current I_D 5÷10 A satisfy our specification. The characteristics are standard. Appropriate transistors supplied everywhere across the world. Only the Drain-Source resistance R_{DS} needs checking for minimal value. During switch-on mode, this resistance contribute additional heat.

We picked MOSFET switches IRFB31N20D [36] from International Rectifier.

They provide high switching frequency up to 1MHz, low resistance R_{DS} and high Drain current I_D. Table 2 present Absolute Maximum Ratings for MOSFET IRFB31N20D.

Table 2.Absolute Maximum Ratings for MOSFET IRFB31N20D.

	Parameter	**Max.**	**Units**
I_D @ T_C = 25°C / T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	31/21	A
I_{DM}	Pulsed Drain Current	124	
V_{GS}	Gate-to-Source Voltage	± 30	V
P_D @TA = 25°C	Power Dissipation	3.1	W
P_D @TA = 25°C	Power Dissipation(with heatsink)	200	
dv/dt	Peak Diode Recovery	2.1	V/ns

As seen from Table 2 all values fully comply with our specification. Even small-sized low-voltage fan supply doesn’t require any heatsink attached to transistor.
Figure 16 illustrates outside view and dimensions for IRFB31N20D.

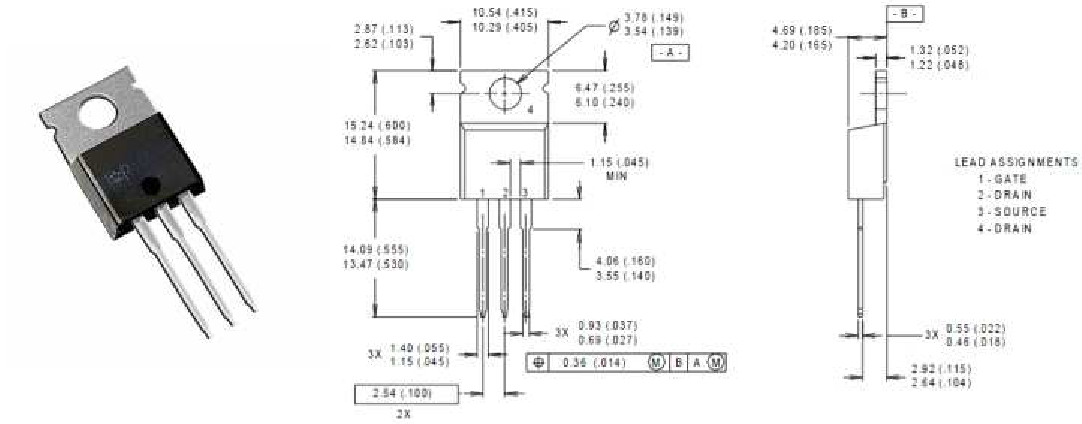

Figure 16.Outside view and dimensions for IRFB31N20D.

3.4.6 Cooling fan

We assumed to use usual a small-sized fan with embedded rpm sensor. This class’s fans utilize 12V DC with nominal current nearly 0.1 A, and a rotational speed around 5000 rpm. EKL AG [37] delivers a wide range of cooling fans on the market. The product line includes small-sized fans for IT solutions. Selected fan [38] matches our specification. Figure 17 illustrates fan’s outside view and Table 3 informs about fan’s characteristics.

Figure 17. Cooling fan for Heater Lab Kit.

Table 3.Cooling fan general specification

<table>
<tr><td>Operating Voltage</td><td>DC 7.0 V ÷ DC 13.2 V</td><td></td></tr>
<tr><td>Rated Power Consumption / Rated Current</td><td>0.84 W / 0.07 A</td><td rowspan="2">±10%</td></tr>
<tr><td>Rotational Speed</td><td>5300 rpm</td></tr>
</table>

3.4.7 Power supply unit

Power supply unit has to convert main power AC voltage to a low DC voltage. Sections 3.4.2 and 3.4.6 specify 5 VDC and 12 VDC as obligatory.
The voltage of 12 Volts may be transformed to 5 Volts with some additional circuitry. Therefore, only 12V DC required for functioning of the kit. Fortunately, there is some class of Power Switches on the market honoured to participate in our competition. IT area offers a class of Power Switches intended to power ATX type motherboards. They deliver voltages in range from 3.3 V to 12 V DC. Even ordinary ATX PSU has enough capability to satisfy all our requirements. Above all, a PSU purchased in EU have already obtained CE marking. We owned one with rated power 480W. Figure 18 illustrates ATX PSU.

Figure 18.ATX Power Switch.

Mentioned PSU intended to use with PC control only. It raises a problem of integrity to our project. Regarding to the PSU's specification, the green wire "POWER ON" to be grounded for local control implementation. Double pole illuminated rocker switch installed to PSU for manual switching.

4 PRACTICAL HARDWARE IMPLEMENTATION

4.1 Circuit block diagram

Before start drawing schematic immediately we found a circuit block diagram as a convenient way to represent our schematic in view of block components. The circuit block diagram based upon the Heater Lab Kit's functional block diagram shown in Figure 12. Particular requirements addressed to system design in Section 3.3 taken into account as well. Figure 19 represents the lab kit's circuit block diagram.

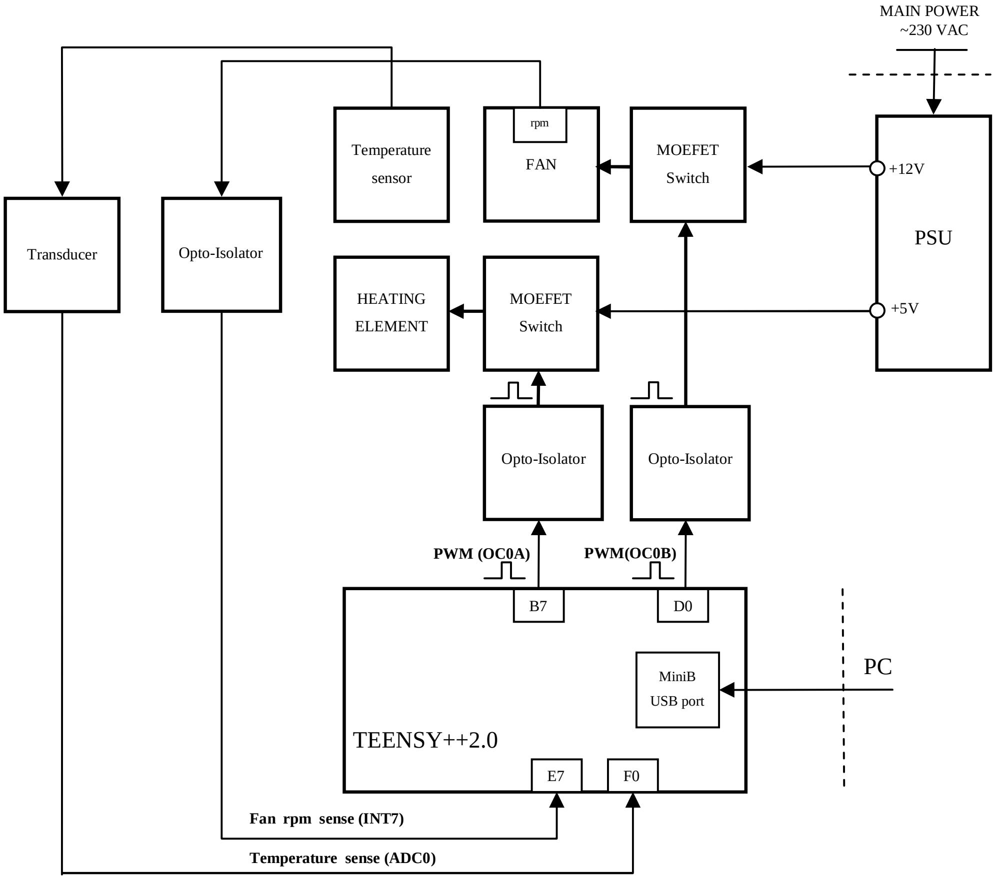

Figure 19.Circuit block diagram.

As seen from diagram above, additional opto-isolators [39] added to design to ensure the PC and microcontroller's health. In round brackets shown addressed inputs/outputs of core microcontroller AT90USB1286 [28].

4.2 AT90USB1286 MCU's modules implementation

4.2.1 Main specification survey

Only general either dedicated to our design features of AT90USB1286 highlighted. Complete specification may be found in related datasheet [28].

Teensy++2.0 USB development board includes a minimal hardware design, thus inputs and outputs of microcontroller addressed directly to related inputs and outputs of the board. Teensy++2.0 board's schematic diagram attached in Appendix 1.

AT90USB1286 is a low-power CMOS 8-bit microcontroller based on the Atmel® AVR® enhanced RISC architecture. The microcontroller provides eight ports with eight pin each. Most of the pins may be configured as either inputs or outputs with addressed functionality. In commonly, ports assigned from PA (PORT A) to PF (PORT F) and pins from Px0 to Px7 with appropriate port's assignment letter. Sometimes pins referred according their functionality: pin PE7 referred as INT7, AIN.1 or UVcon. The MCU clocked from either external crystal or internal oscillator. Teensy++ provides external clocking 16MHz.

In order to provide lower frequency an internal prescale unit used to divide supplied frequency in proportion to 2, creating division factors 2, 4, 6,....., and 256.

Ports on Teensy++2.0 board correspond directly MCU ports, only "P" letter removed. Hereby, MCU port PF addressed to port F on the board, and MCU's pin PE7 addressed to pin E7 on the board.

In the next sections, we make a brief tour through all involved modules: ADC module temperature detection, 8-bit Timer/Counter0 for PWM control and Timer/Counter1 module for fan's rpm sensing.

4.2.2 Analog-to-Digital Converter module

AT90USB1286 supports successive approximation ADC with a 10-bit resolution. Eight pins of port F connected over 8-channel multiplexer to ADC allowing eight voltage inputs.

ADC supplied by a voltage applied to AV_{CC}, which must not differ more than ±0.3V from V_{CC} where the main control voltage applied. In Teensy++2.0 board AV_{CC} and V_{CC} already have common and supplied both from USB. Additionally, internal voltage 2.56 V is alternative to AV_{CC}. They used as reference voltage for ADC. The pins configured for either single-ended mode or differential mode. In single-ended mode input voltages refer to 0V (GND) and provide declared resolution. In deferential mode, PF1 (ADC1) pin is common for other port F related pins and, so, this mode provides seven differential channels with only 8-bit resolution. Some other modes applied. Please refer to specification.

In our case, the addressed pin is ADC0 (PF0) in single-ended mode. Internal voltage 2.56 V used as ADC reference voltage.

4.2.3 8-bit Timer/Counter0 with PWM

AT90USB1286 supports 16-bit Timer/Counter1 and Timer/Counter with PWM, but no needs to use precision PWM in our case. 8-bit Timer/Counter0 supports two independent Output Compare Units providing Fast PWM and Phase Correct Modes.

Module equipped with a prescale unit and division factors 1, 8, 64, 256 and 1024 provided.

Generally, the Timer/Counter0 (TCNT0) counts impulses until matching occurs with the value set in either OCR0A or OCR0B registers. Depending on modes, the voltage across reserved pins set or cleared. Pins OC0A (PB7) and OC0B (PDO) reserved for PWM control and may act as either inverted or non-inverted outputs. Hereby, four modes of PWM are accessible. Please, refer for details to dedicated sections in main specification.

In our case, the Phase Correct Mode with non-inverted outputs OC0A and OC0B chosen.

4.2.4 Timer/Counter1 for fan's rpm sensing

Timer/Counter1 is a 16-bit timer/counter. The Timer1 (TCNT1) counts impulses are 2^{16} = 65536. If maximum achieved, Timer1 resets to zero and starts counting again on the next cycle. The value of Counter1 updated if near the addressed pin event occurs while Timer1 counting. Time interval between two events measured and calculated by multiplying the Timer 1 value and duration of one impulse. The event occurs due to voltage detecting proceed in various ways. Please, refer to dedicated section in main specification.

In our case, counting addressed to pin INT7 (PE7) and voltage detected upon rising edge of input voltage.

4.3 Transducer's circuitry

Transducer's circuitry proceeds from requirements imposed by temperature sensor Pt100 and ADC resolution. Temperature detected upon voltage across Pt100. As temperature rises, the resistance of Pt100 raises almost linearly according to the equitation of M.S. Van Dusen:

Equation 4-1

$$R = R_0 \bullet (1 + A \bullet T + B \bullet T^2 + (T\text{-}100\ °C) \bullet C \bullet T^3)\ ,$$

where: R_0 is sensor's resistance near 100°C;

T is temperature in °C;

A = 0.003908;

$B = -5.775 \bullet 10^{-7}$;

$C = -4.18 \bullet 10^{-12}$;

For temperatures above 0°C the equitation simplified to the formula:

Equation 4-2

$$R = R_0 \bullet (1 + A \bullet T + B \bullet T^2).$$

The Heater lab Kit intended to use for temperatures above 0°C. Hence, the simplified formula of the equitation of M.S. Van Dusen used for all related calculations.

As seen from the formula, small non-linearity occurs with known behaviour. In order to provide reliable temperature detection the voltage across sensor should rise in the same manner as resistance. According the Ohm's law:

Equation 4-3

$$U_R = I_R \bullet R.$$

Hence, voltage rises in the same manner as resistance in case if the current passing through sensor is constant. Passing current also limited in maximum value at 7 mA. The passing current also limited in minimum value by ADC capability to sense minimal changes in measured voltage. The minimal sensed change in voltage V_{min} referred to ADC quantum level affected by ADC resolution N and reference voltage V_{ref} and found as follows:

Equation 4-4

$$one\ quantum = \frac{V_{ref}}{(2^N - 1)}.$$

Taking into account that N = 10 and V_{ref} = 2.56V, the calculated value for 1 quantum equals to 2.54 mV, which is minimal sensed voltage change or, in other words, V_{min} = *one quantum* = 2.54 mV. Following the Ohm's law the minimal required passing current I_{min} calculated as follows:

Equation 4-5

$$I_{min} = \frac{V_{min}}{\Delta R_{Pt100}},$$

where the ΔR_{Pt100} corresponds the minimal measured temperature change or temperature resolution. Resolution 1 °C is enough for educational purposes. The Table 4 displays ΔR_{Pt100} calculated according to Equation 4-2 for each interval of 100°C in range 0°C - 300°C.

Table 4.Pt100 resistance's values nominated to 1°C in range 0 - 300°C.

T, °C	R_{Pt100}	*Range,°C*	ΔR_{Pt100}	V_{min}, V	I_{min}, A
0	100.00	0 -100	0.385025	0.0025	0.006493
100	138.50	100-200	0.373475		0.006694
200	175.85	200-300	0.361925		0.006908
300	212.04				

As seen from Table 4 the temperature interval between 200°C and 300°C dictates the value for I_{min} that must be at least 7mA. Summarizing all arguments, the next requirements designated for circuitry:

- Measuring current must be constant;
- Measuring current maximal value limited at 7 mA;
- Measuring current minimal value limited at 7 mA;

In order to avoid some errors due to electrical noise, the measuring current should be more than 7 mA acting as some kind of gain according to Equitation 4-3. As current rises, the self-heating problem arises. However, in case of constant current, the self-heating characterized by the linear relationship as follows:

Equation 4-6

$$T_{s\text{-}h} = C \bullet R \bullet E,$$

where $T_{s\text{-}h}$ is self-heating value in °C;

$C = I^2$=const and I is a measuring current;

R is a resistance of Pt100;

E is a self-heating coefficient in °C/mW;

Self-heating compensated with appropriate calculations as follows:

Equation 4-7

$$T = T_{measured} - T_{s\text{-}h}$$

E specified in sensor's specification [35] in range from 0.02 to 0.2 in connection with certain conditions are airflow or water. Isolating sensor from ambient keeps self-heating coefficient within an evaluated value and self-heating compensated during calculations.

Self-heating coefficient can vary from system to system. In our case, the self-heating coefficient E evaluated at value E = 0.3 °C/mW during experiments.

The 3-Terminal Adjustable Current Sources LM334 [40] implemented in schematic to provide constant measuring current in range 7 – 8 mA. The design arranged by specification, and related schematic shown in Figure 20. The schematic referred as "ZERO TEMPERATURE COEFFICENT CURRENT SOURCE". Resistors R7 and R8 define the current I_{set} flowing across Pt100. The relationship described in specification and represented within our schematic by next equitation:

Equation 4-8

$$I_{set} = \frac{V_{R7}}{R7} + \frac{V_{R8} + V_{D2}}{R8}.$$

$V_{R7} = V_{R8}$ = 67.7 mV as defined in specification. The voltage across diode D2 V_{D2} = 0.6 V. If R7 = 18 Ω and R8 = 180 Ω, then

Equation 4-9

$$I_{set} = \frac{67.7mV}{18\Omega} + \frac{67.7mV + 0.6\,V}{180\Omega} = 7.47mA\ .$$

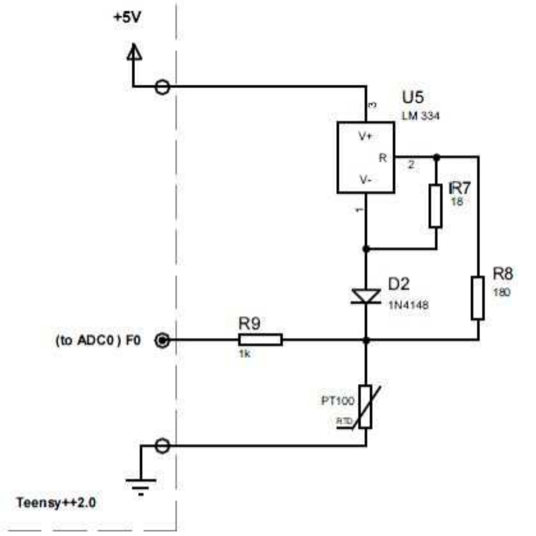

Figure 20.Transducer design based on LM334 adjustable current source.

4.4 PWM control and fan’s rpm sense schematic

4.4.1 Heating element with PWM control schematic

The schematic based on standard solutions for PWM control with MOSFET switches. Figure 21 shows schematic solution for PWM control in this project.

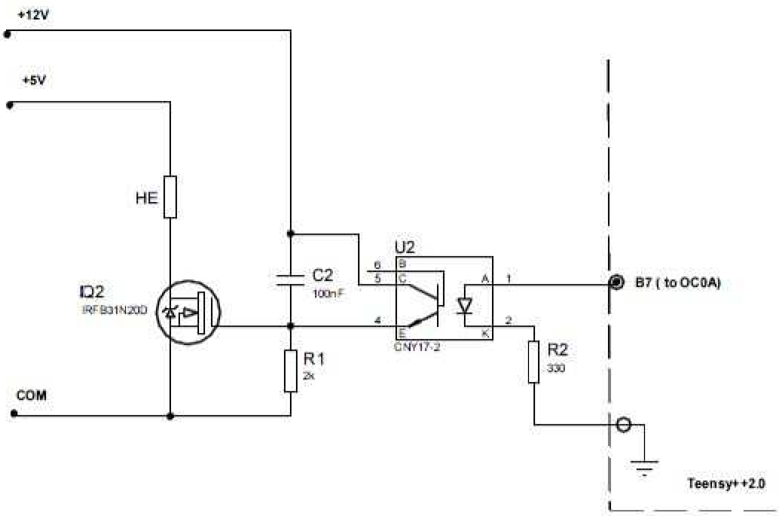

Figure 21.Schematic of heating element’s PWM control.

The optocoupler U3 (CNY17-2) isolates electrically the MCU circuitry from external supply. Resistor R2 limits current across the optocoupler. According to the optocoupler's specification [41] recommended current is near 16 mA. Taking into account that MCU supplied by USB voltage, R2 chosen to nominal 330Ω in order to limit flowing current at 15 mA. Maximum current across MCU's pins must not exceed 40 mA. Thus, related requirements arranged in this design. Capacitor C2 grounds alternate currents imposed due to PWM implementation. R1 provides voltage reference for MOSFET. 12 V applied to Gate input then optocoupler passes the current. Voltage across MOSFET switch V_{DS}= 5V and Drain-Source current

$I_{DS}= V_{DS} / R_{element} = 5V / 2.9\Omega \approx 1.72$ A. Purchased wirewound resistor's measured resistance was $R_{element} = 2.9\Omega$.

4.4.2 Fan's PWM control and rpm sensing schematic

Figure 21 shows fan's PWM control and rpm sensing schematic.

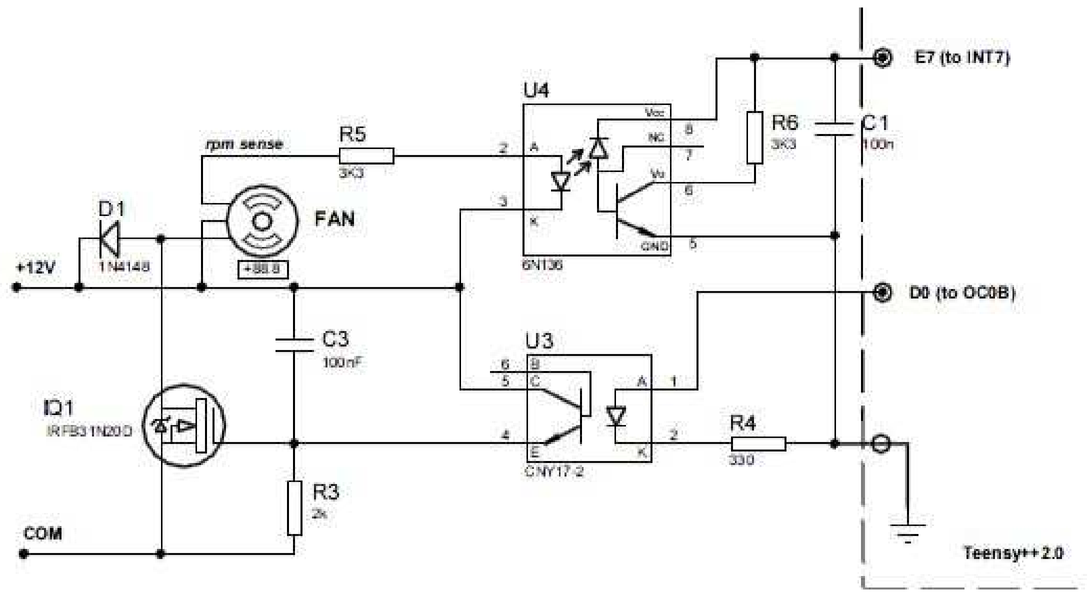

Figure 22.Fan's PWM control and rpm sensing schematic.

As seen from figure above, the same solution for fan's PWM control schematic realized as for heating element. Only a few changes applied. Fan supplied from 12 V supply line. Diode D1 routes back motor inductive spikes, when PWM low.

Fan sensing provided by embedded sensor with open collector. Current applied across the sensor must not exceed 5mA. To comply this requirement the resistor R5 = 3.3 kOhm inserted in schematic, providing sensing current I_{sense} = 12V / 3.3kΩ ≈ 3.6 mA.
Optocoupler U4 used of other modification than for PWM control schematic. The optocoupler 6N136 provides high performance and has output collector output [42], used as a usual on/off switch to deliver fan's sensor impulses to MCU's pin INT7. Optocoupler's output schematic includes R6 to limit current flowing through the pin.

4.5 Heater lab Kit's final design

At the final stage, the hardware design prototype tested on breadboard. Figure 23 illustrates prototyped design on breadboard.

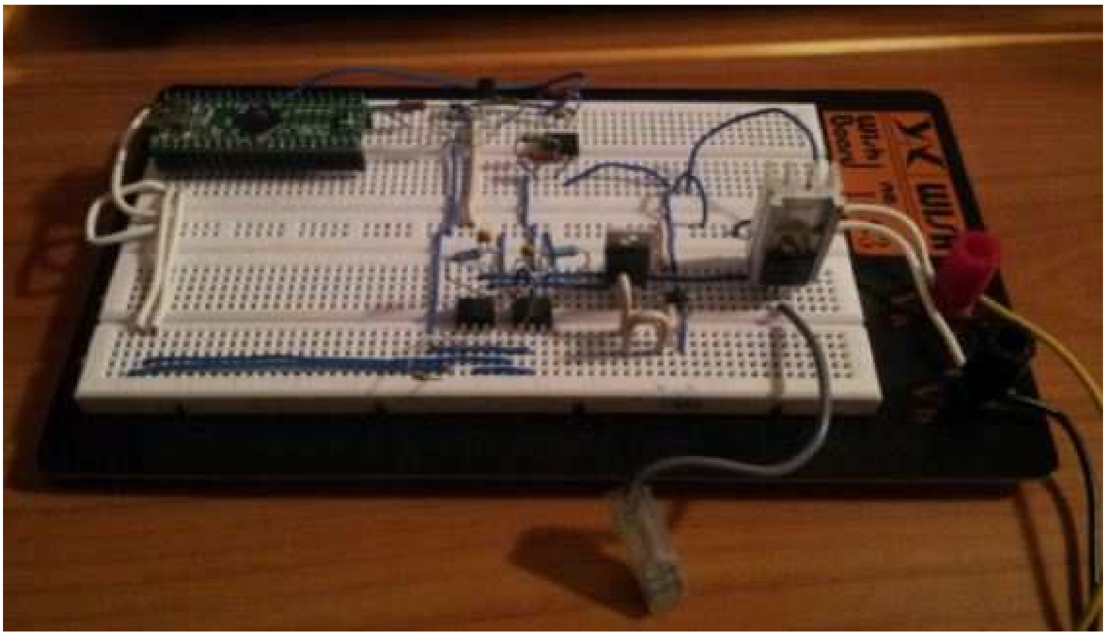

Figure 23.Heater lab Kit's prototyped design.

The prototyped design used during ADC calibrating work, software development and debugging. The final schematic implemented auxiliary pin headers. The *J1, J2, FAN* and *TA* provided interface between Teensy++2.0 board, fan and temperature sensor and PCB. The pin header *SUPPLY* used for power supply interface between PSU and PCB. The schematic redrawn to arrange necessary connection, some components rerouted and replaced. The final circuit diagram attached in Appendix 2. The Bill Of Materials attached in Appendix 3. Then schematic is tested, the PCB layout prepared ready for fabrication.

The PCB layout attached in Appendix 4. For PCB fabrication used some handmade techniques [43]. The result illustrated in Figure 24.

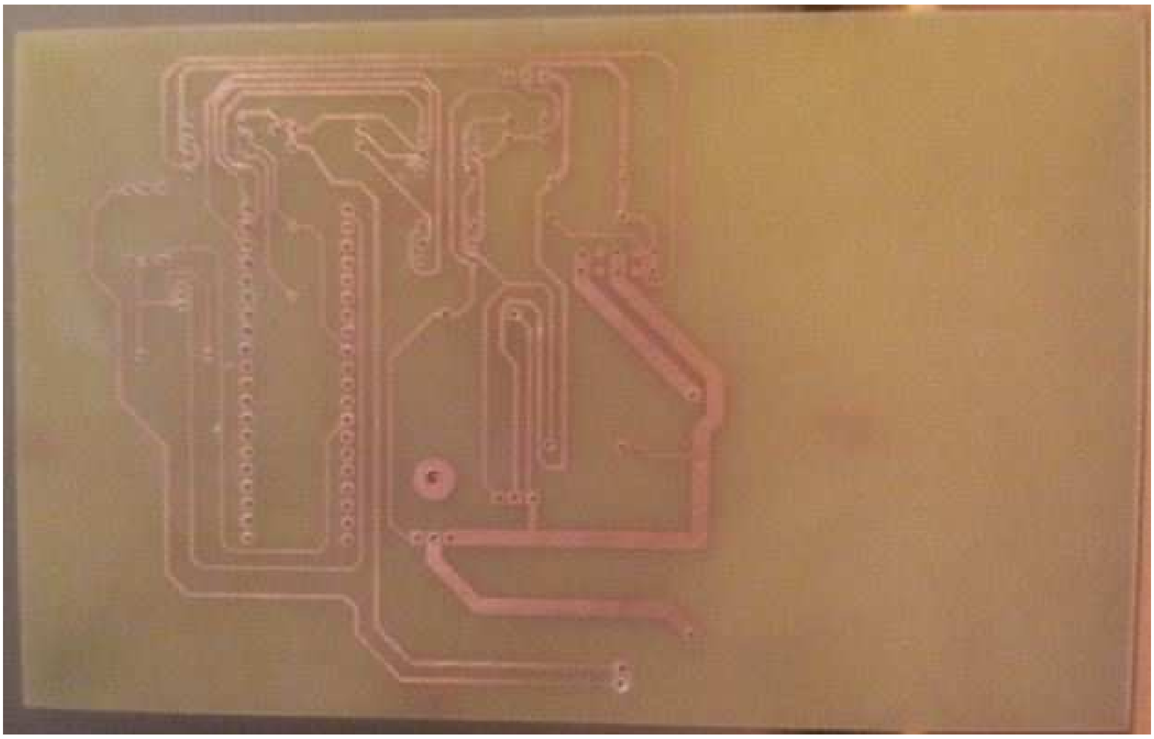

Figure 24. Fabricated PCB with already drilled pin holes.

The Heater Lab Kit outside view without case illustrated in figure 25.

Figure 25.The Heater Lab Kit outside view without case .

Figure 25 illustrates kit's final design

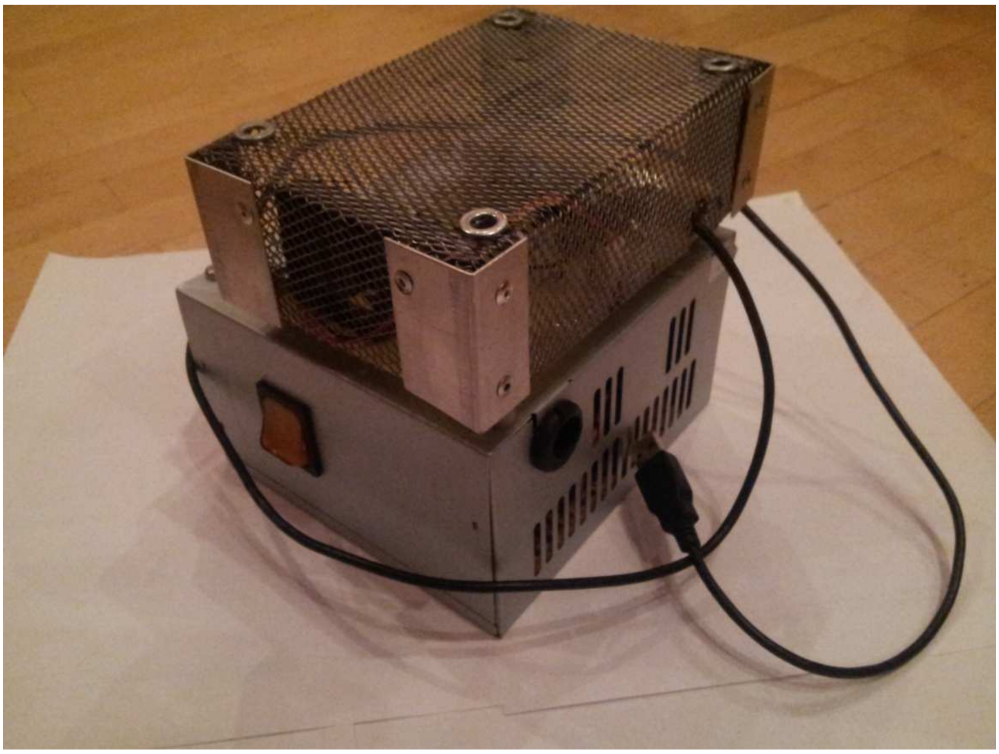

Figure 26. Heater Lab Kit as made.

5 SOFTWARE DEVELOPMENT

5.1 Main notes

The work based on MCU AT90USB1286 [28] main specification and some examples of code [45] from Teensy++2.0 supporting site. Particular details regarding to MCU structure observed enough in various section. For efficient coding AVR035 [46] application note from Atmel Corporation implemented.

5.2 Major milestones

At the beginning of code design, some simple code implemented to lunch ADC routine and check for inconsistency in hardware design. New project created in Atmel Studio version 5. Stage1. Special macros created to simplify bit operations. Macros placed in header file *"bit_operations.h "*. The initial code included main routine programming, ADC related registers setting and USB messaging implementation for initial data request with HyperTerminal [44]. The Equitation 4-2 used to derive the formula of temperature in dependence on sensor's resistance which looks as follows

Equation 5-1

$$T(R_{Pt100}) = \frac{-A + \sqrt{A^2 - 4B(1 - \frac{R_{Pt100}}{R_0})}}{2B}$$

where: T is temperature in °C;

R_0 = 100 Ω;

A = 0.003908;

$B = -5.775 \cdot 10^{-7}$;

Figure 27 illustrates debugging messages in Hyper Terminal's window

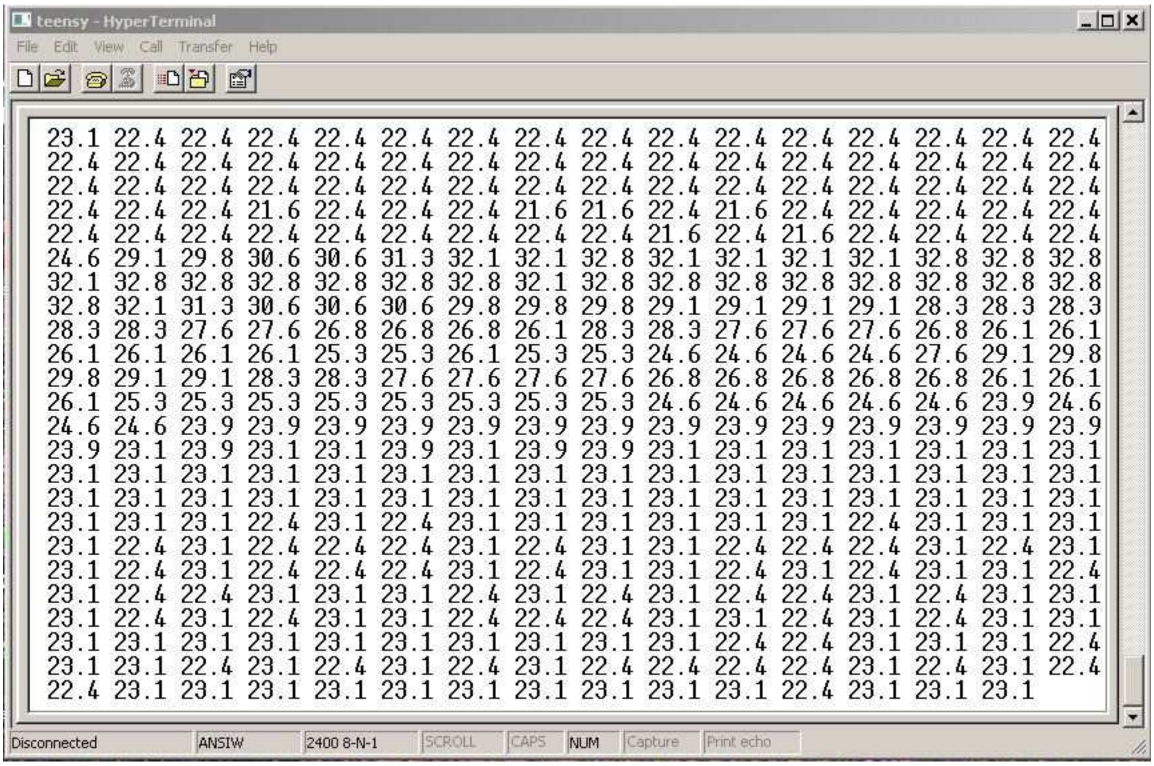

Figure 27.Debugging messages in Hyper Terminal's window.

Stage 2. ADC module needed calibration due initial errors. The calibration's procedure considered in Section 5.3. After calibration performed, calibration table created to avoid floating point calculations as recommended.

Stage 3. PWM control programming started. Fan rpm sensing applied. This last required a lot of efforts applied for code optimizing and debugging due to fan's sensor particular features in aspect of PWM control implemented to power fan. The fan sensor designed as outputs with open collector, and signal grounded for some time interval. The interval be measured by Timer/Counter1 using interrupts. The rpm sensor allows counting while powered. However, when PWM control is low, fan is not powered and revolutions not sensed while turning around. The special method "Pulse Stretching" implemented to count impulses while fan's power is off. The main idea is to power fan for some small interval only for necessary amount of pulses counted. Figure 28 illustrates sensor's output waveform.

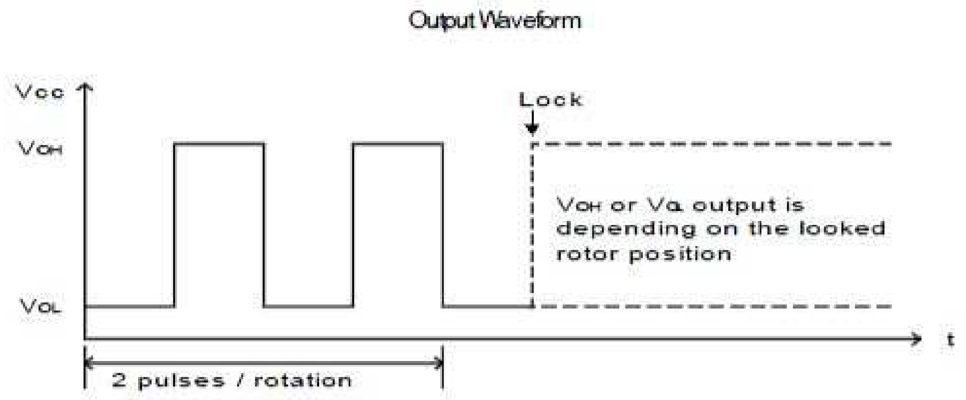

Figure 28.Fan sensor's output waveform.

As seen from figure above only two pulses or three falling either raising edges to be detected to calculate rpm. For PWM duty cycle 50% given near 3000 rpm. In order to count rpm we needed to switch PWM to 100% for at least time interval 60sec/3000 = 20msec.

Even if this method doesn't provide precision measurements, we can evaluate rpm for informative purposes.

Stage 5. USB-to-Serial particular interface developed for data exchange with PC. The targeted environment Simulink includes the toolbox Real-Time Windows Target [47] that supports real-time data exchange through serial protocols. Simulink modelling environment together with specified hardware board forms hardware-in-the-loop simulation giving a great benefit in learning how real system act. Modelling environment may be configured fast for particular needs of an experiment.

Stage 6. Practical experiment conducted to confirm kit's functionality

5.3 ADC calibration

ADC calibration's procedure described in AVR120 Application Note [48].

ADC calibration needed due to the total error of the actual ADC contributed by either the offset error or gain error. Offset error found using flowchart shown in Figure 6 of mentioned application note. The main idea is in raising of input voltage until first quantum detected. Thus, offset error = real input voltage – quantum voltage. Variable resistor 10Ω Used by this part of calibration. In our case, offset error = 4.54mV – 2.5 4mV = 2mV

Then offset error compensated and gain error found next. The procedure also described in Figure 8 of the same application note. The idea is in dividing of voltages to get some ratio and, thus, calculated measurements repaired using this ratio. The experiment conducted near ADC voltage reference value. One voltage detected by ADC and another is actually measured value. The experiment required a variable resistor near 300 Ohm. The gain error received is 1.004. Besides ADC calibration, the self-heating coefficient evaluated as well.

At the end, final equitation for temperature detection looks as follows

Equation 5-2

$$T(°\mathrm{C}) = \frac{-A + \sqrt{A^2 - 4B(1 - \frac{1.004 \cdot 0.00254 \cdot Code_{ADC} - 0.002}{100 I_{set}})}}{2B}$$

This kind of calculations not recommended in real-time and look-up table created with pre-calculated values as function T = f($Code_{ADC}$). The look-up table resides in *adc_calibration.c* source file All actual measurements made with the multimeter DVM890L.

5.4 Program's functional modules

Heater Lab Kit's each function realized in its own programming module where one header file and one source file included. The Table describes modules and their functional tasks.

Program files	***Functionality***
main.c, main.h	Main program input, main routine following and data flow control
adc.c, adc.h	ADC initializing and ADC code delivering. All functions called from main routine
adc_calibration.c, adc_calibration.h	Look-up table keeper; temperature value returned on request from main routine
pulse_counter.c, ulse_counter.h	Related interrupts handling, pulse stretching handling; rpm counted and calculated on request from main routine.
pwm.c, pwm.h	PWM control initialization and performing on request from main routine
usb_serial.c, usb_serial.h	USB-to-Serial data transmit support. All function called from main routine. Free software routine supplied by Teensy++ manufacturer
prescale.h, bit_operations.h	Macroses included to simplify coding

The files' printouts attached in Appendix 5.

5.5 Program flowchart

Figures 29 – 32 refer to four program flowcharts. Flowcharts 1 and 2 depict mainly the general routine, whereas Flowchart 3 refers to fan rpm filtering and Flowchart 4 mainly shows the routine of PWM duty cycles changing.

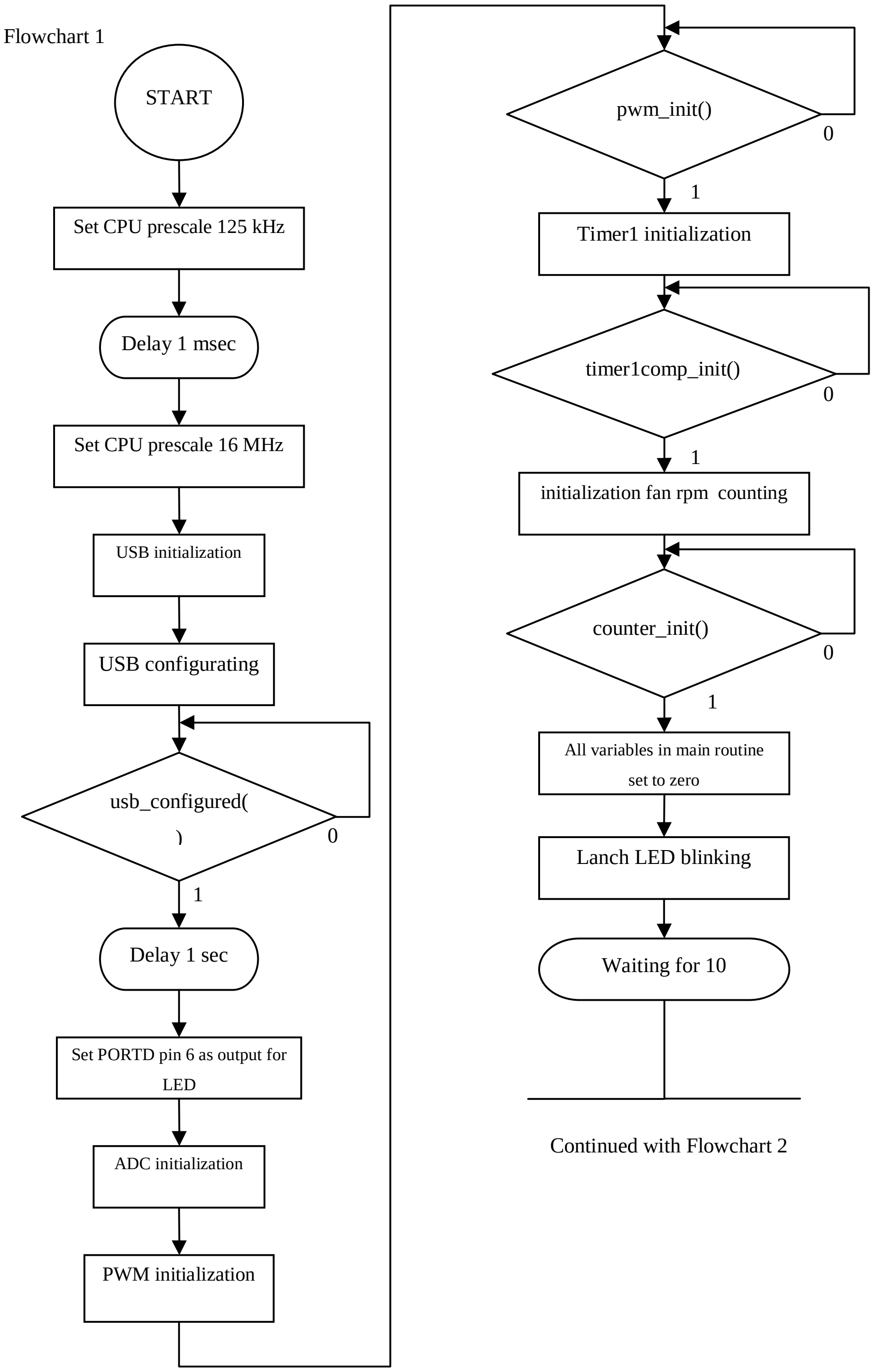

Figure 29.Program Flowchart 1.

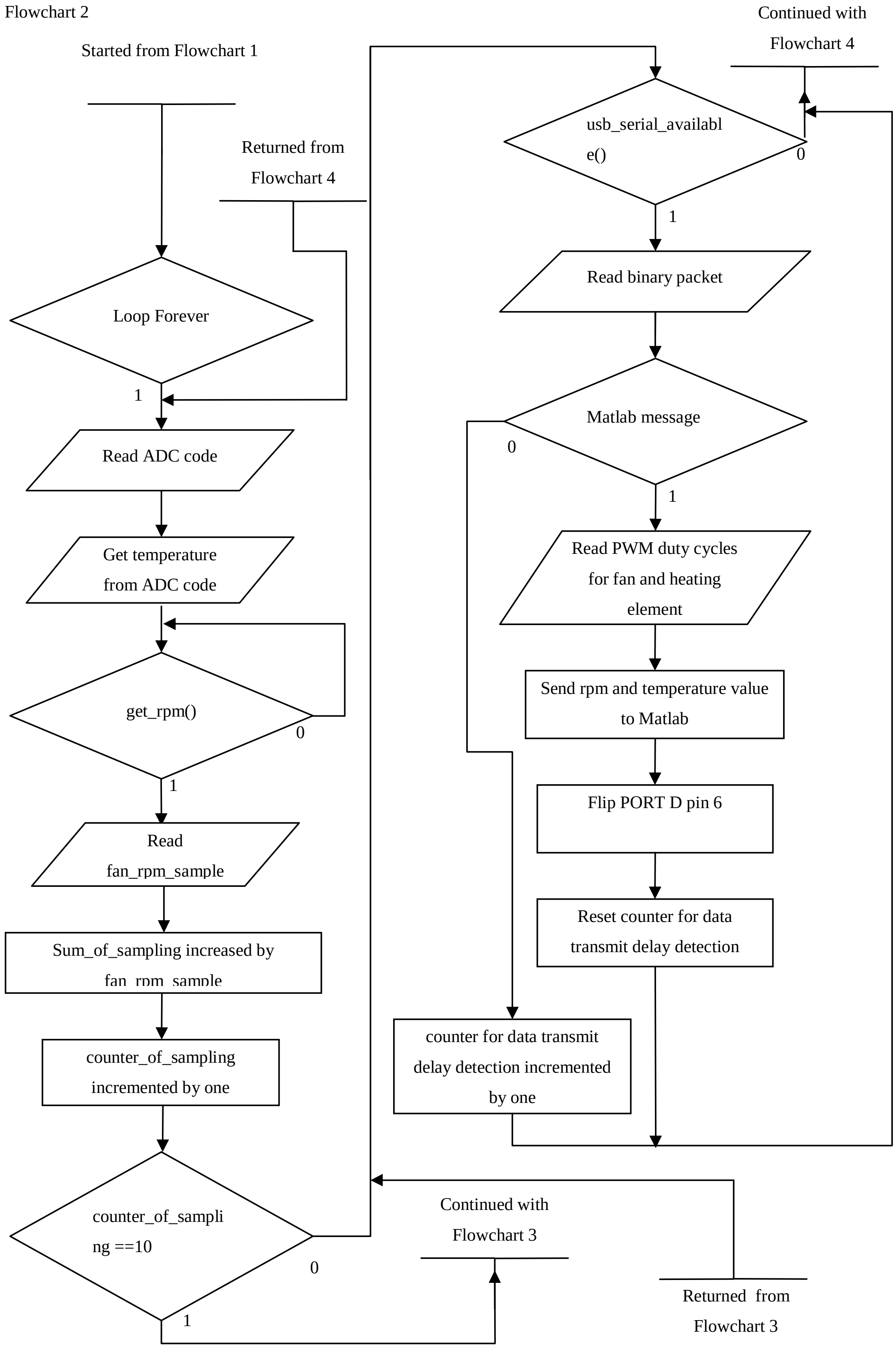

Figure 30,Program Flowchart 2.

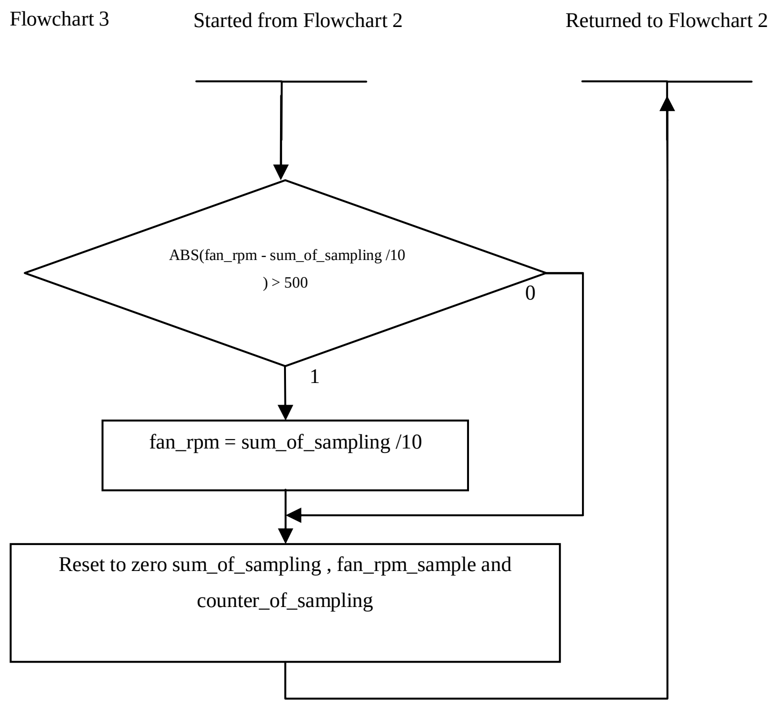

Figure 31.Program Flowchart 3.

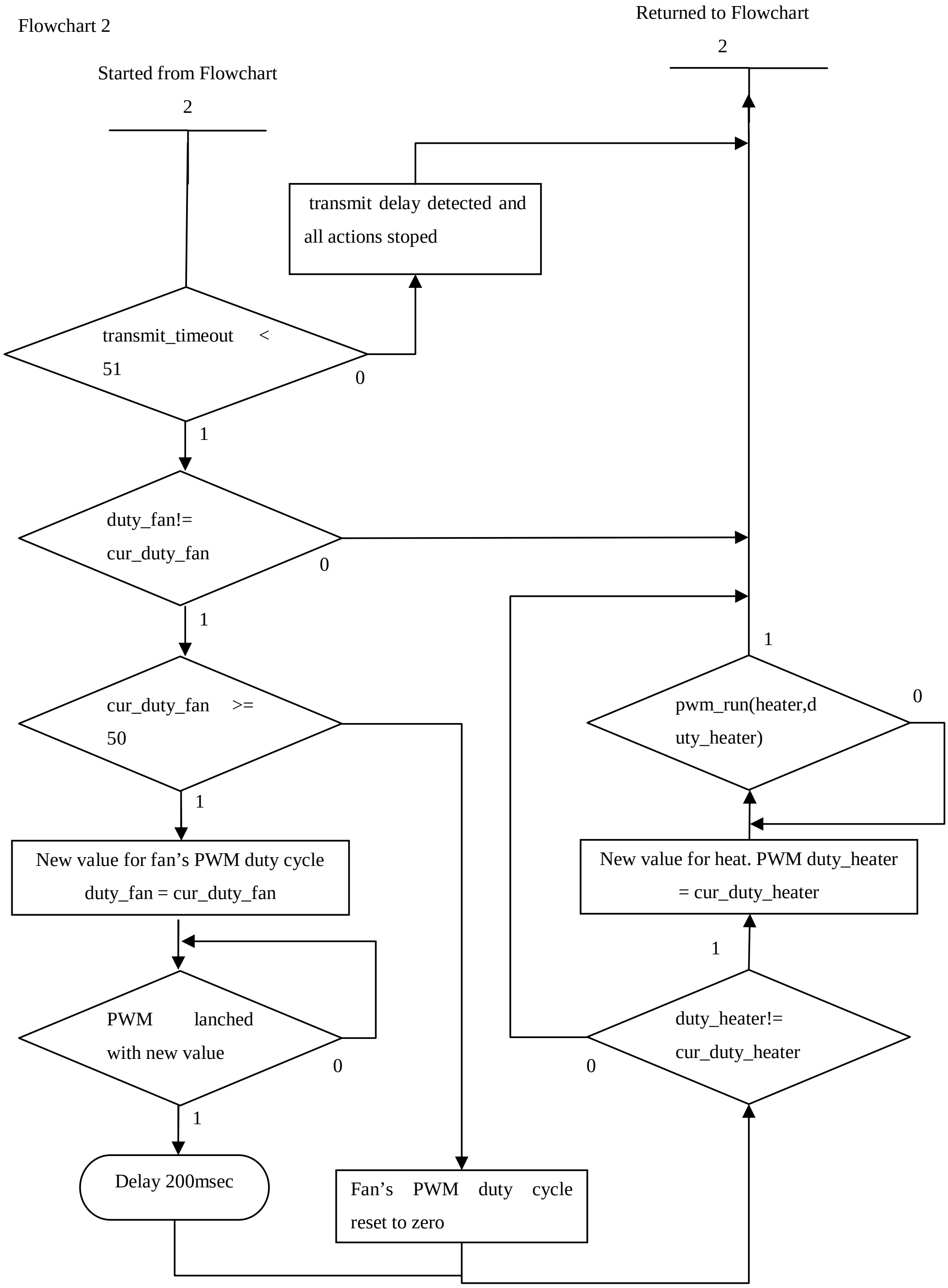

Figure 32.Program Flowchart 4.

6 PRACTICAL IMPLEMENTATION

6.1 Heater Lab Kit modelling in Simulink

Simulink provide Real-Time Windows Target toolbox to support simulation in Simulink environment with real physical objects as Heater Lab Kit is. Experiments conducted in real-time limited by maximal data acquisition frequency at 20 KHz in external mode. However, 20 KHz is enough for most of experiments in control theory studies. In our experiment in temperature control no needs to utilize all scope of performance. Thermal processes behave in slow manner, and data acquisitioning two times per second brings enough information to identify an object characteristic and control the object's behaviour from Simulink with implementation various blocks and tools. Packet Input and Packet Output block used to receive and send unformatted binary data. Main conception of data exchange between Simulink and Heater Lab Kit proceed from sending request for data to the kit's control system. Thus, a experimenter defines the data acquisition frequency by himself. Requested data sent and received in some format already defined during practical experiments. Each packet consists of a number of bytes, which varies in dependence on direction data sent. Each packet consists of two main blocks: control block and data block. The size of each control block is the same for both directions and equals to one byte. Control blocks provide identification if either Simulink or Lab kit send data. Data blocks vary because of size of data sent. Simulink sends only PWM duty cycles' values forming data packet of three bytes. Data sent by Lab Kit include, besides the control byte, the temperature and fan's rpm values reserving five bytes. The Tables describe the data packets particular features.

Table 5.Data packet sent by Simulink

bytes	**3**	**2**	**1**
variable	PWM heater	PWM fan	MATLAB id
value	0...255	127...255	0xAA

Table 6.Data packet sent by Lab Kit.

<table>
<tr><th>bytes</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th></tr>
<tr><td>variable</td><td colspan="2">temperature</td><td colspan="2">fan's rpm</td><td>Lab Kit id</td></tr>
<tr><td>values</td><td colspan="2">0.....65536</td><td colspan="2">0.....65536</td><td>0xBB</td></tr>
</table>

The model of Heater Lab Kit illustrated in Figure 33.

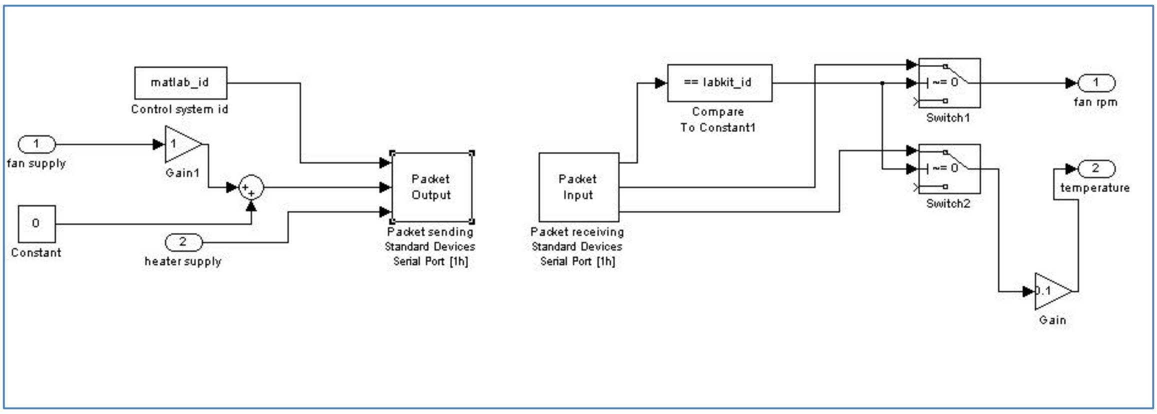

Figure 33. The Heater Lab Kit's model in Simulink

The experiment itself provided by modelled system shown in Figure 34

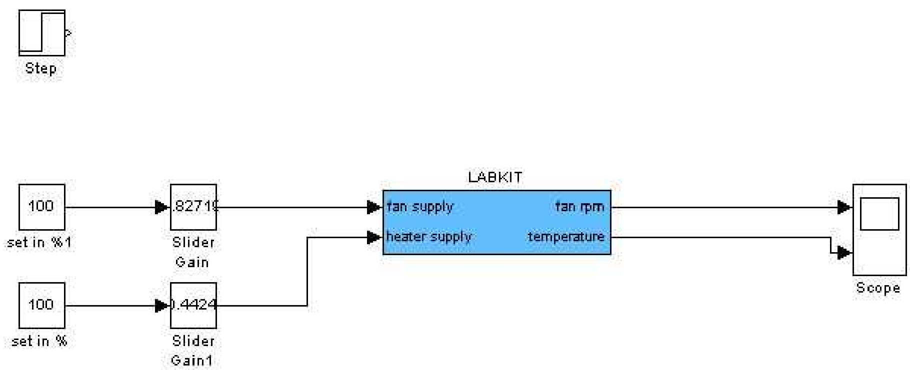

Figure 34. Modelled experiment system representation in Simulink.

For experiments with object identification, the step block implemented . After, the model of the thermal plant identified and the PI controller tuned using the FOMCON toolbox for MATLAB [49] . Figure 35 shows addressed to object's characteristics plot.

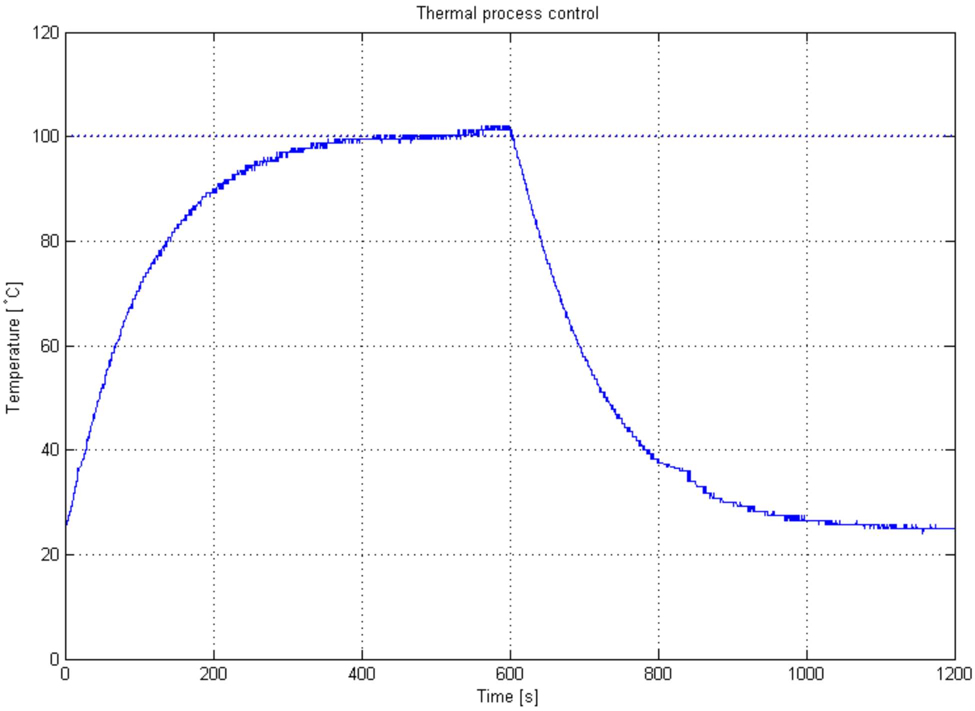

Figure 35. The identified object's characteristics plot.

7 DEVELOPMENT ENVIRONMENT

7.1 IDE in context of embedded design

Before starting of hardware installations, especially for embedded systems, an important scope of work done on stage of schematic design based on virtual simulation and software debugging in connection with already created component base. Herewith some components may be added or removed, and code created and optimized while system debugged and tested. Hence, much of the low-level design work minimized. A developer has a choice to make a set of IDE according to system complexity, implemented microcontroller's family and own preference in code developing work. Our preferred set consists of Atmel® Studio IDP [39], and another great debugging and simulating platform Proteus VSM version 7.1 from Labcenter Electronics [40].

Atmel® Studio provides code engineering, debugging and simulation of various MCU families supplied by Atmel Corporation. Atmel Studio includes their own developed ASF [41] library, simulator with a list for supported devices and various tools for emulating of LCD displays and touch screens. Additionally, Atmel Studio integrated with open-source compilers.

Proteus VSM provides schematic design, supported MCU simulation in connection with component selection and program loaded in MCU. Additionally, it allows a PCB layout design.

All main features of mentioned IDE/IDP in the next sections, and considered in context of this work.

7.2 Proteus VSM

Proteus VSM is a great IDE with capabilities of mixed-mode SPICE circuit simulation [42] to control hardware design's compatibility, and of code debugging tools with extended visibility and analyzing facilities. In others words, a developer equipped with a good-level virtual laboratory for hardware design. Proteus VSM integrated with schematic capture ISIS software [43] and ARES layout software [44] for PCB design. It includes a rich library of built-in SPICE3 primitives for emulating of various passive and active electronic devices as resistors, capacitors, transistors, operational amplifiers etc. Circuit printouts for PCB design added. Moreover, the primitives of new circuits released on the market and compatible with SPICE3 version may be imported to the library for simulation. We would recommend some starter kit of Proteus VSM to use in educational laboratories engaged with embedded design.

Proteus also includes an impressive library of MCU from various manufacturers providing an universal development environment. Enough scope of Atmel's microcontrollers supported by Proteus VSM as well. Moreover, Proteus VSM simulator may be integrated with Atmel® Studio 4 and used as an optional simulation tool.

The workflow of embedded design in Proteus VSM development environment proceeds as follows:

1. Schematics created in ISIS environment. A supported MCU must be added if necessary;
2. A program loaded to MCU in hexadecimal file format;
3. Some virtual measurement instruments, or signal sources may be added;
4. Run near real-time simulation with source code debugging, MCU's registers and program variables observation;
5. Necessary changes to schematic or code inserted, simulation started again;
6. Ready schematic exported to ARES environment for PCB design,
7. Due to restrictions in PCB design some changes may be implemented and imported back to ISIS;
8. BOM list created on your choice;
9. PCB layout ready for fabrication;

Large-scale project may require high-performance workstations due to extensive CPU load during simulation. Some screenshots added in some sections to illustrate the workflow in this particular project. Only few options tested in scope of this thesis. All interested addressed to developer's website [45] for complete information and available quotes.

7.3 Atmel® Studio

Another fine tool, extensively used for MCU learning and code programming and debugging in this particular project, was Atmel Studio of versions 4 and 5.

Atmel® Studio of version 4 supports AT90USB1286 microcontroller either with default simulator from Atmel or with integrated Proteus VSM simulator. Additional benefit of Proteus VSM simulator concludes in linkage selected MCU to concrete circuitry, allowing code writing, compiling, and debugging and system simulation upon particular design from one place. It was the main reason to use the version 4. However, this version has poor coding assistance and some compiler troubles already removed in the next versions.

Atmel® Studio of version 5 obtained all necessary coding assistance tools for fast code developing and compiling, but options for emulating of AT90USB1286 and some other MCU models excluded.

Thereby, Atmel® Studio of version 4 used for code debugging and circuitry simulation and Atmel® Studio of version 5 implemented mainly for code engineering, final compiling and debugging with USB support.

7.4 IDE implementation in current project

We continue with a few figures illustrating the main stages of IDE implementation in Heater Lab Kit's development. Figure 19 illustrates preliminary Teensy++ schematic copied from original [46] and realized in ISIS environment.

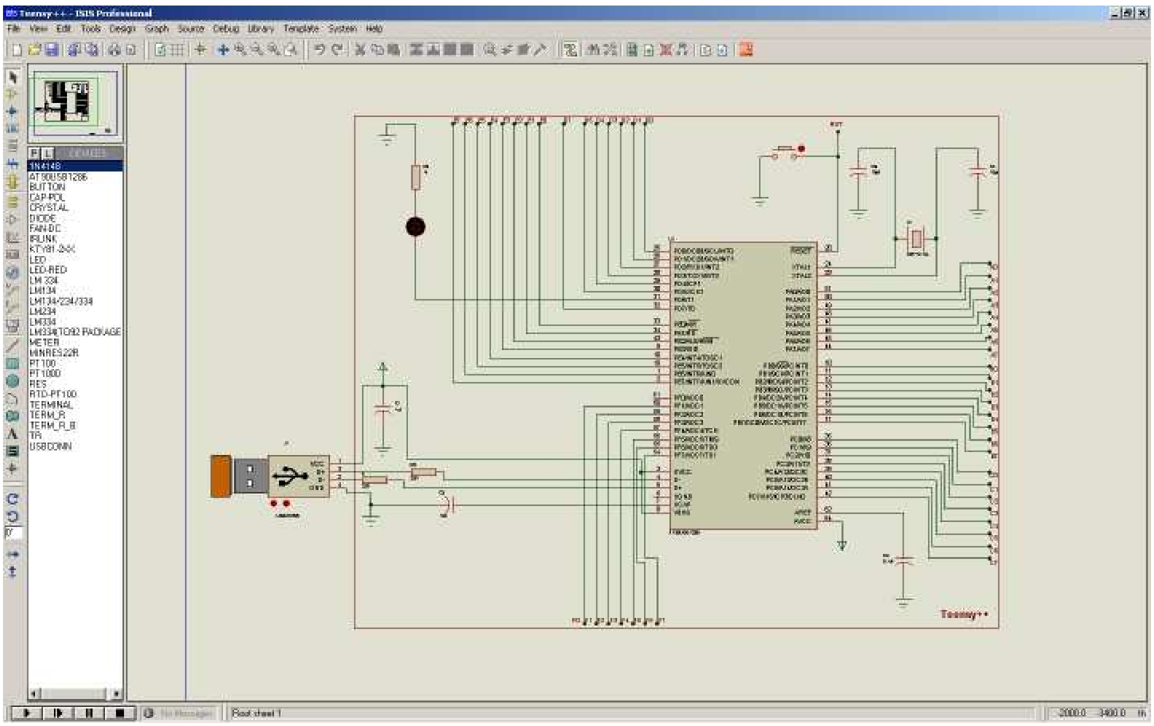

Figure 36.Preliminary realization of Teensy++2.0 schematic in ISIS environment.

On left from Teensy++ recognized USB socket. That is original product USBCONN developed by Labcenter Electronics and intended to emulate USB connection between real PC and emulated MCU. The tool accompanied with USB protocol's analyzing tools.

Next is Figure 20 illustrates one of the stages of schematic development.

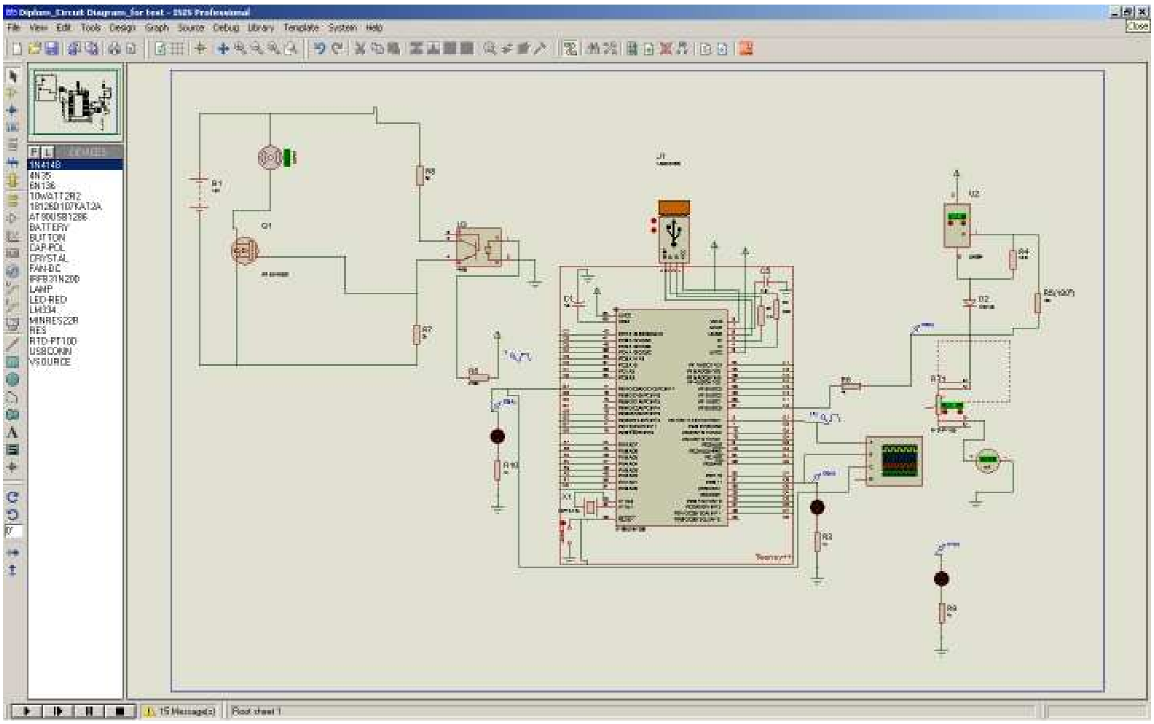

Figure 37. Schematic developed for learning purposes.

Figure 21 illustrates a simulation of input signal delivered to MCU's input INT7 served for fan impulses counting as discussed in dedicated to software development sections.

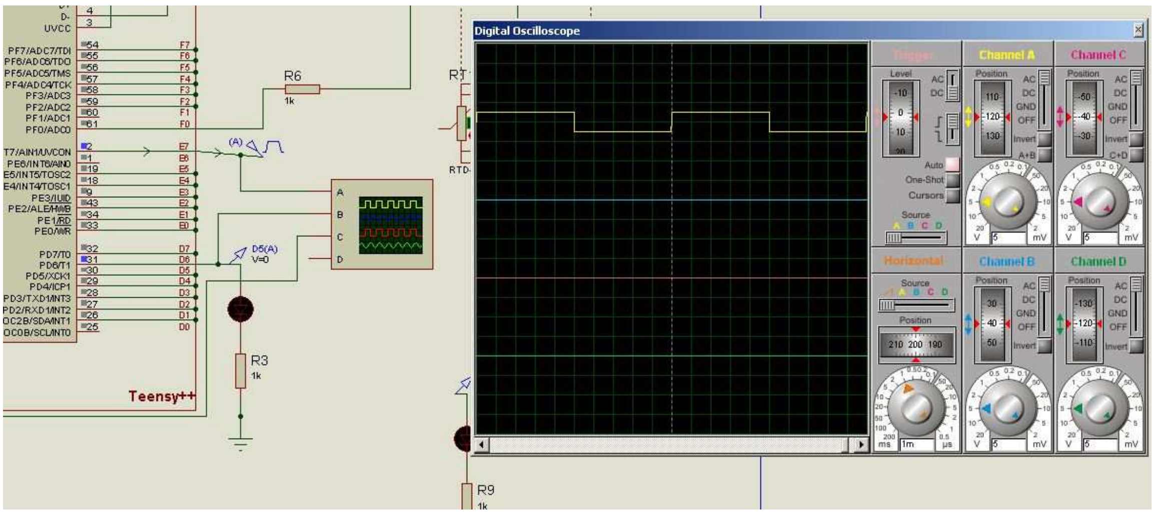

Figure 38.At90USB1286 input signal simulation.

As seen from Figure 20, the Teensy++ schematic redrawn closer to original, but not fully copied due to differences in behaviour of real existing object and simulated primitives. Some devices recognized as a motor (animated), MOSFET switch, optocoupler, oscilloscope etc. Seen on Figure 21 oscilloscope visualizes the signal delivered to INT7.

Figure 22 illustrates main workspace of Atmel Studio 4.0 with integrated Proteus VSM simulator and automatically generated ISIS workspace on left.

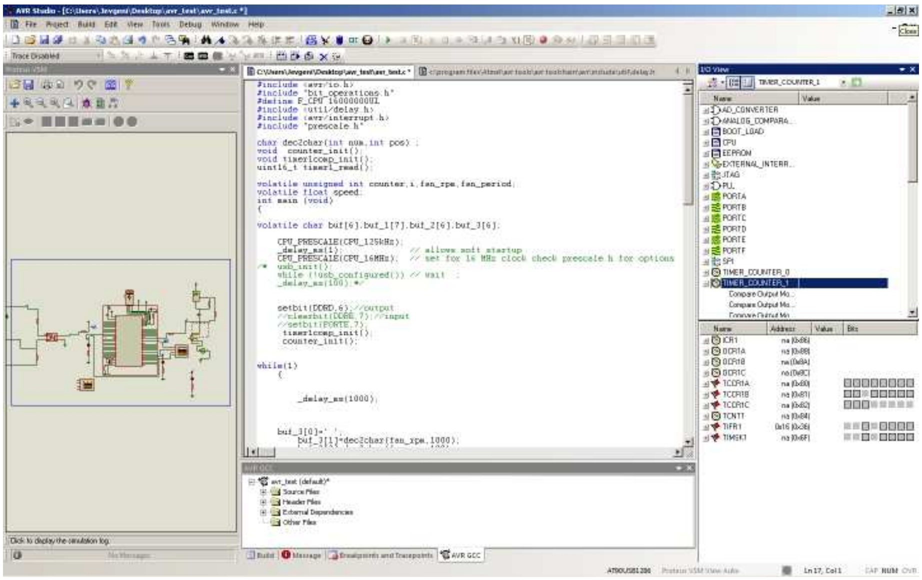

Figure 39. Main workspace of Atmel Studio 4.0 with integrated Proteus VSM simulator.

Figure 23 illustrates a simulation routine in the same workspace.

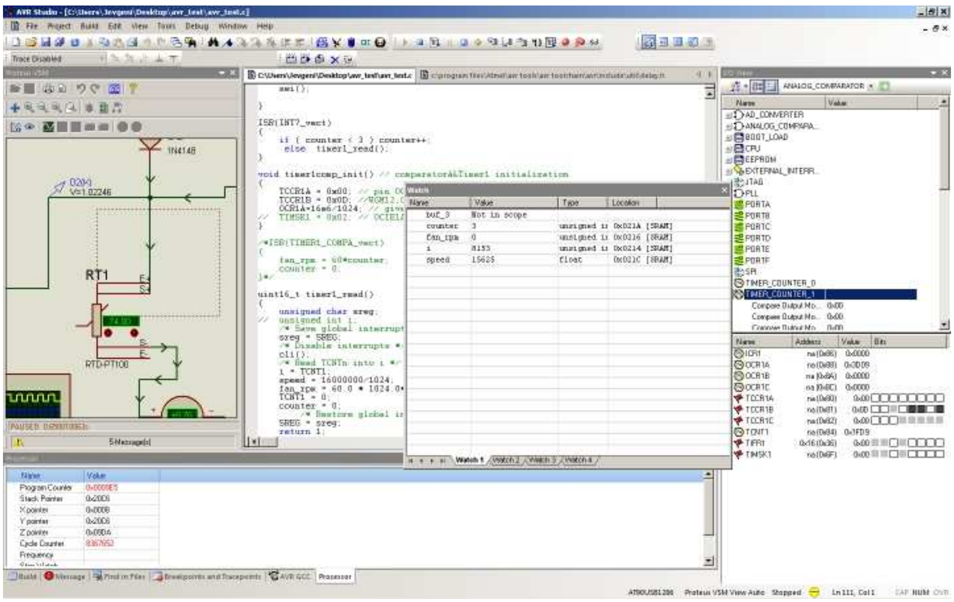

Figure 40.Atmel Studio 4.0 and Proteus VSM simulation in action.

If a developer intended to use Proteus VSM simulator, he requested for related design file with ISIS capture. File opened on left pane and changes to schematic applied without any affect to original file.

When development work is close to the end, the final actions focused on PSB layout design. A PCB layout design routine described here with appropriate illustration accompanied. At the beginning, ISIS schematic exported to ARES with one mouse click and main ARES window appeared. A developer customizes a PSB dimension and places all components with Auto Placer or each component manually to PCB space. Auto Router used to draw paths. If some conflicts detected manual redirection or replacing required for proper design. Figure 24 illustrates Heater lab Kit's final schematic adapted to PCB layout design and ready to export.

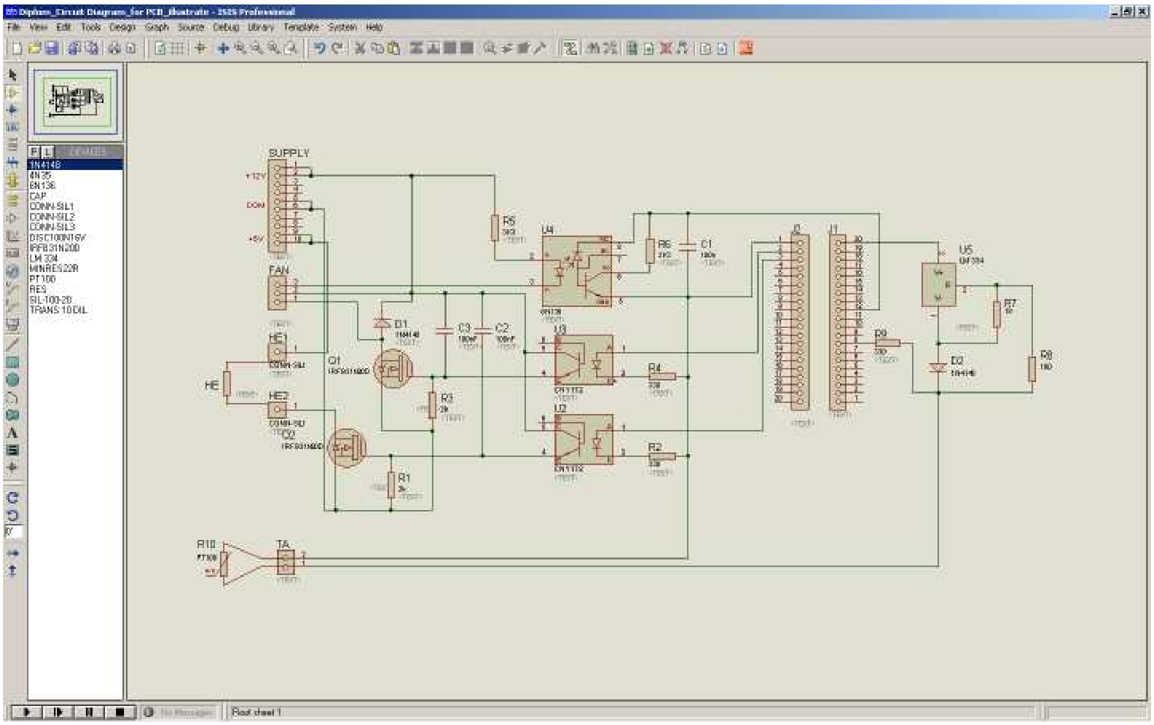

Figure 41.Heater lab Kit's final schematic adopted to PCB layout design.

Figure 25 illustrates already sized PCB layout with two header pin connectors placed manually. PCB edges designated with yellow lines. Due to restrictions to design, some elements placed manually from the beginning. In our case, restrictions imposed by predefined pinout for connectors Teensy++2.0 plugged in.

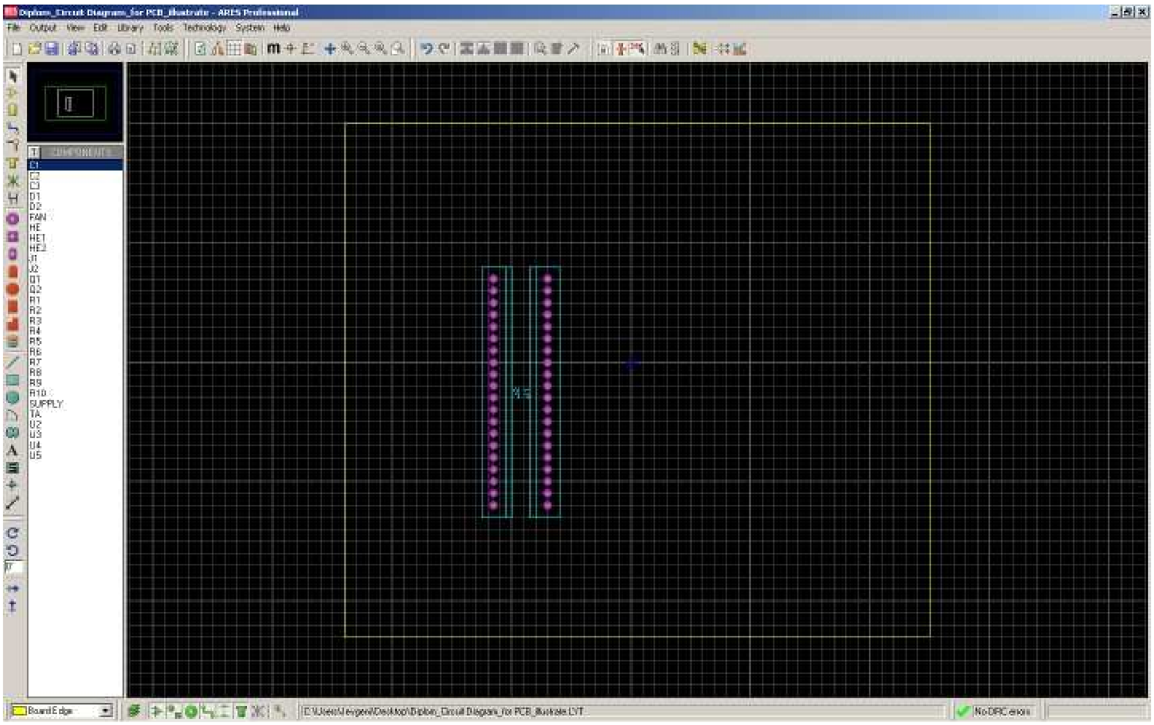

Figure 42. PCB layout with two header pin connectors.

The next, Figure 26 shows the Auto Placer placed all components. Green lines designate connections while yellow arrows directed to optimal placement of a single component.

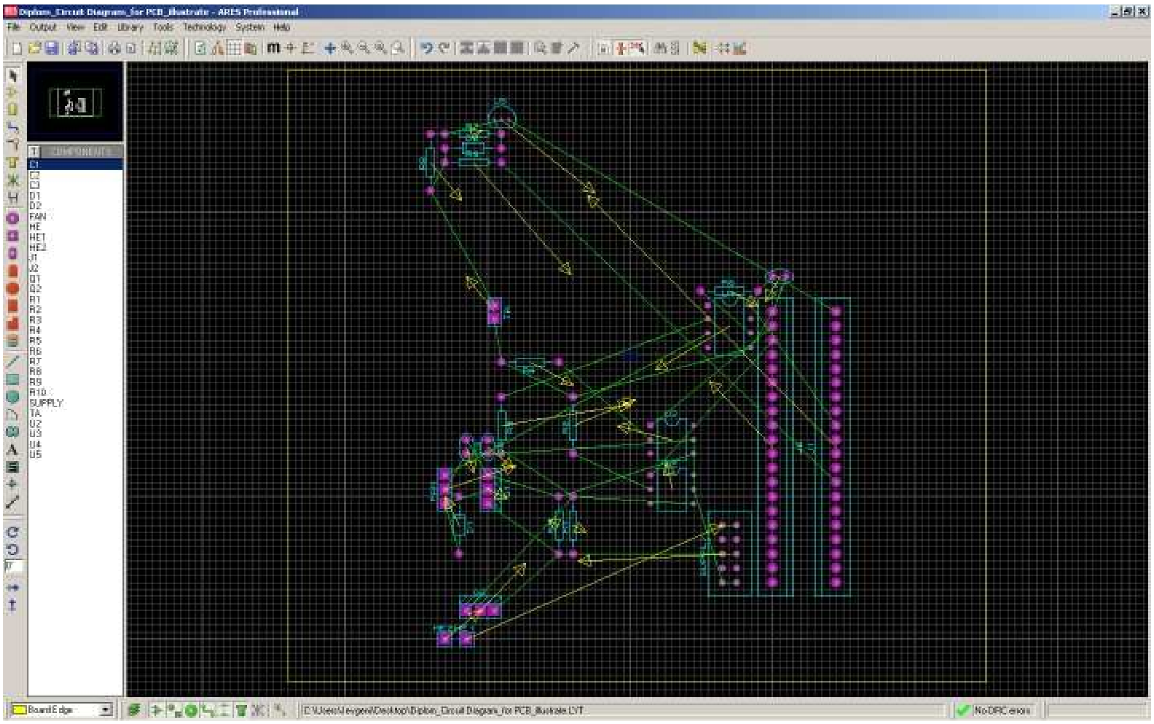

Figure 43. ARES's Auto Placer in action .

Figure 27 illustrates preliminary PCB layout created by Auto Router.

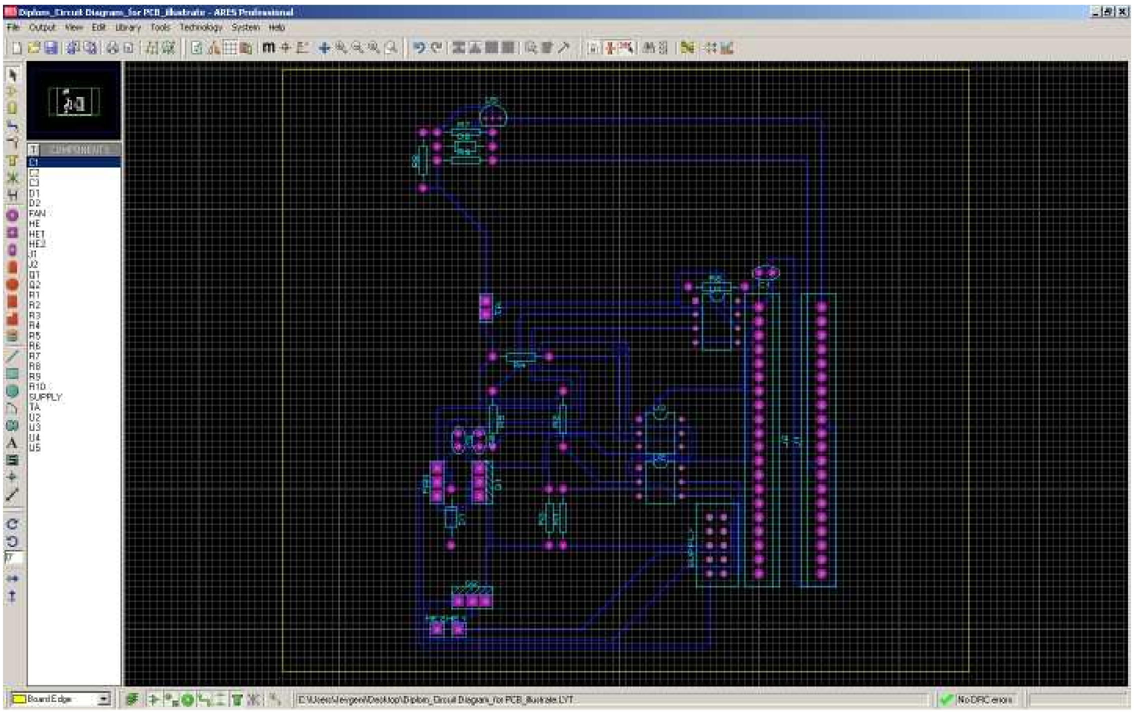

Figure 44.Preliminary PCB layout created by Auto Router.

Not all restrictions applied here. The supply header pin placed too close to Teensy++ board and replaced. The final PCB design looks like that represented in Figure 28.

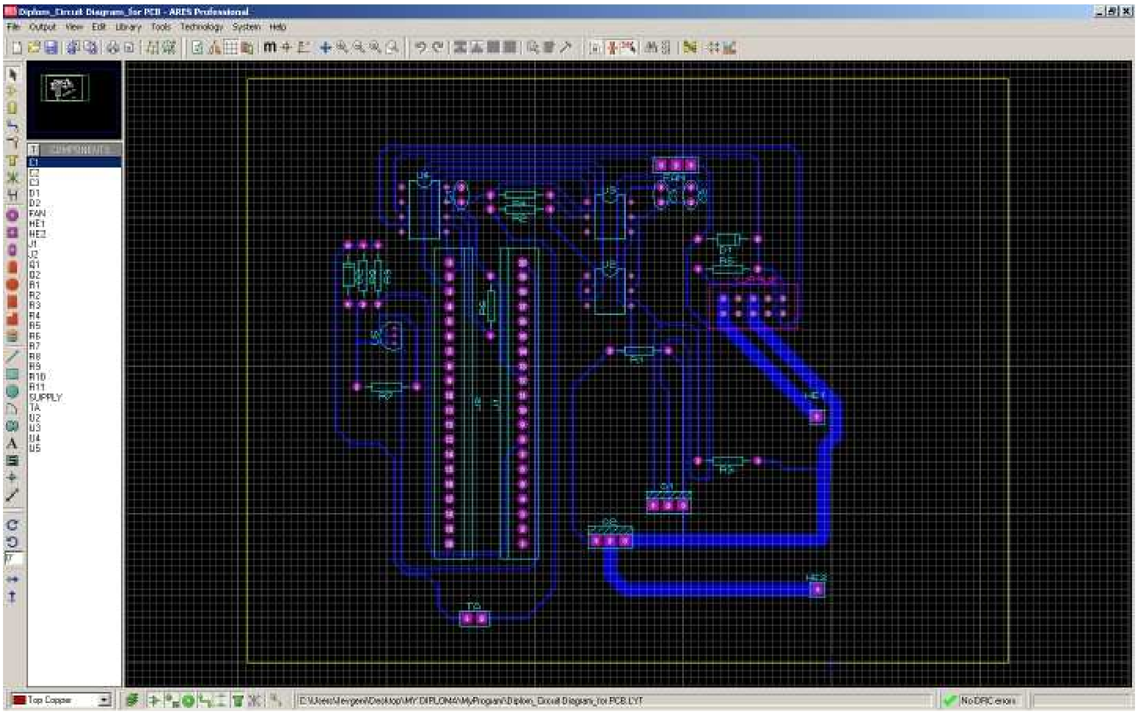

Figure 45.The final PCB layout in ARES workspace.

8 CONCLUSIONS

Four months ago started project successfully finished now and new-fashioned Heater Lab Kit may be used in educational work. The main purpose achieved and new educational facility presented. The scope of work done is great as seen from the list of used literature. During the working with the theme of thesis sent rich and invaluable experience in hardware design, components selection and, of course, software development in context of embedded systems. Bit arithmetic teached a lesson about thinking in category of low-level design forming the engineering mind. Hand-on experience obtained from fabrication excited and challenges for new projects implemented in embedded design. During scope of theoretical work a lot of information filtered, new aspects in laboratory research work found.

Realized laboratory kit operates regarding specification, but the questions about the precision may arise. All measurements provided by a low-cost tester with its own errors in related ranges. The area of electrical noise and ADC theory still needs to be investigated more in connection with implemented schematic and selected components. Experienced, that more attention required to theoretical aspects of control theory.

Inspiring aspects was the cost of components implemented in design. Nothing has been told before about this aspect. Definitely, the cost of designed kit less than 200 dollars and not exceed a 100 euro, but even less. Taking into account our conception and realized kit's performance the ratio of project cost and reserved capabilities for future modernization is great. Only 3% of flash memory consumed and much less of processor time due to recommended software and design implementation. The code accompanied with clear comments and developed with a view of future modules added to the kit.

We have finished with the project, but new project and ideas already can utilize obtained experience.

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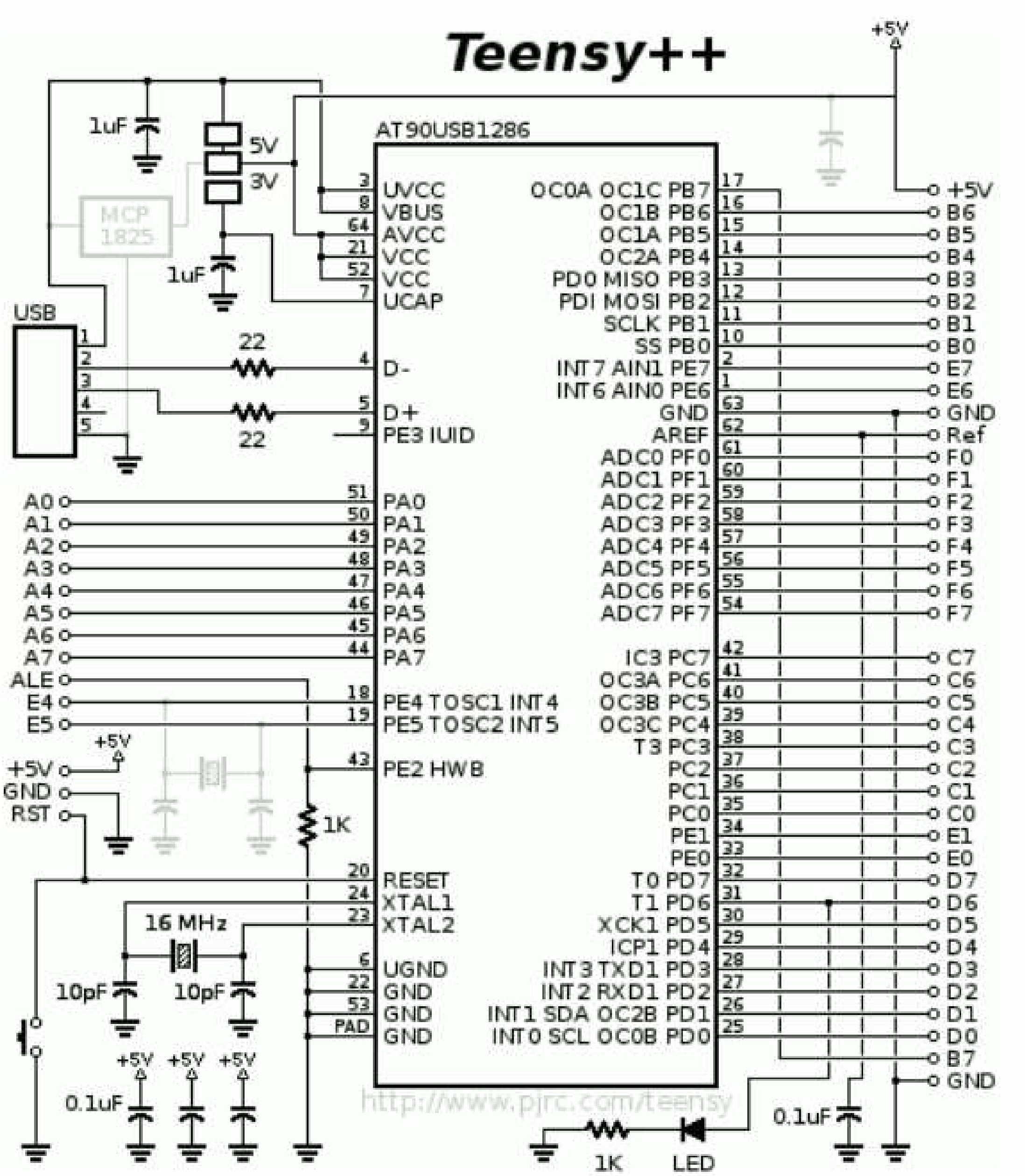
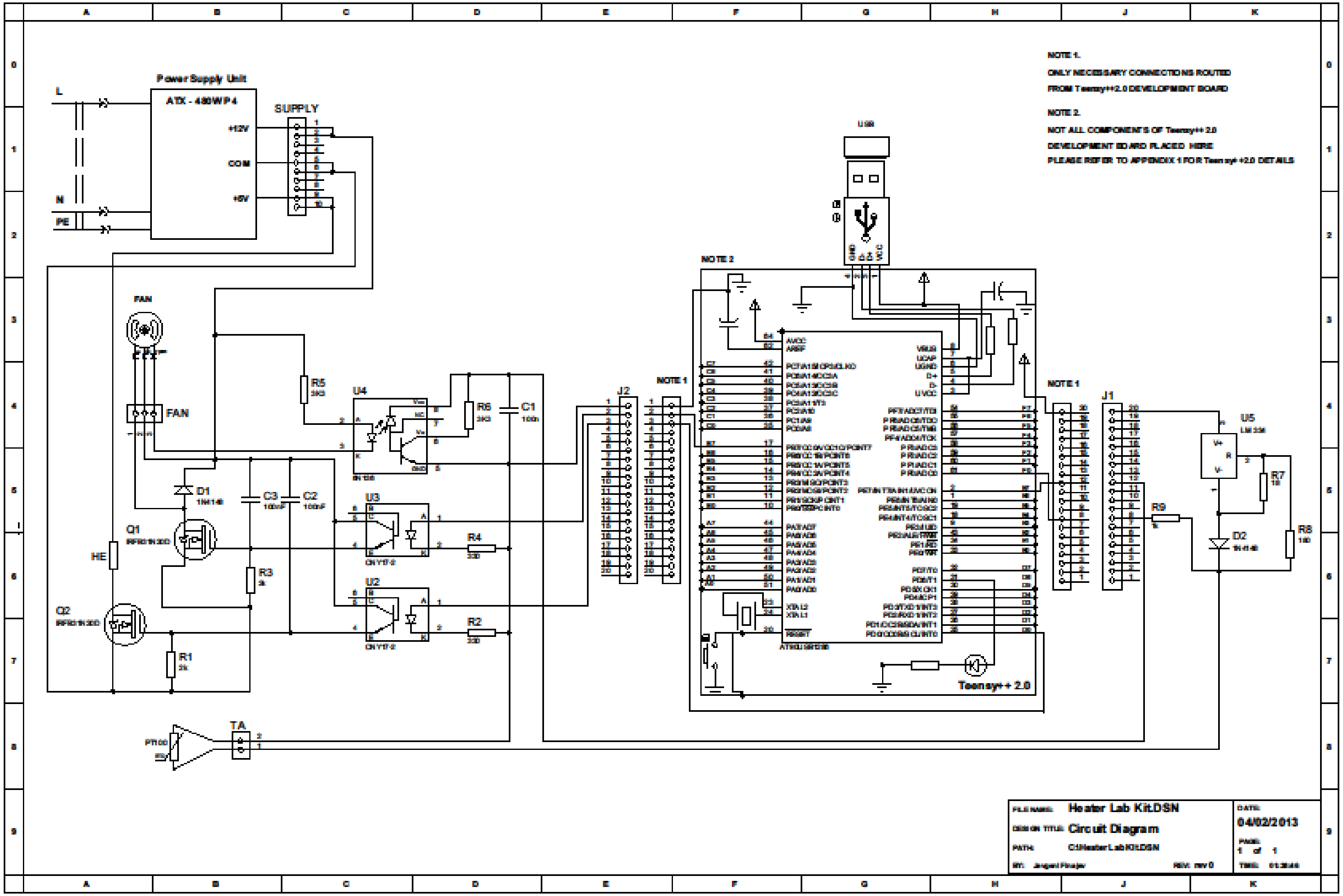
APPENDIX 1.TEENSY++2.0 SCHEMATIC DIAGRAM.



APPENDIX 2. HEATER LAB KIT CIRCUIT DIAGRAM

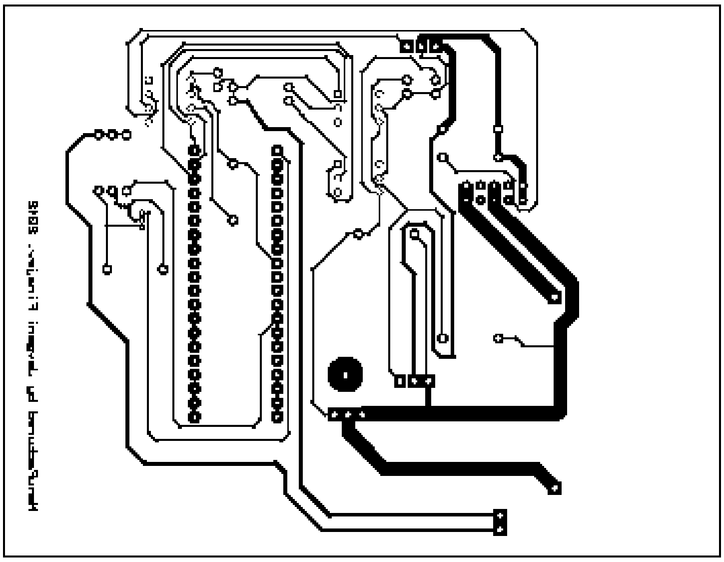


APPENDIX 3.BILL OF MATERIALS

Bill Of Materials
=================
Design: Heater Lab Kit
Revision: rev. 0
Author: Jevgeni Finajev

QTY	PART-REFS	VALUE	PACKAGE
Resistors			
2	R1,R3	2k	
2	R2,R4	330	
2	R5,R6	3K3	
1	R7	18	
1	R8	180	
1	R9	1k	
1	Pt100		
Capacitors			
1	C1	100nF	
2	C2,C3	100nF	
Integrated	***Circuits***		
2	U2,U3	CNY17-2	DIP-6
1	U4	6N136	DIP-8
1	U5	LM 334	TO-92
MCU			
1	Teensy++2.0	USB development board	
Transistors			
2	Q1,Q2	IRFB31N20D	TO-220AB
Diodes			
1	D1	1N4148	DO-41
1	D2	1N4148	DO-35
Pin Headers			
1	FAN	CONN-SIL3	
1	HE	2R2	
4	J1-J4	SIL-100-20	
1	SUPPLY	TRANS 10 DIL	
1	TA	CONN-SIL2	
Miscellaneous			
1	Fan	FD124010MS (1A5K)	40mm
1	Power Supply Unit	ATX-480W P4	

APPENDIX 4 HEATER LAB KIT'S PCB LAYOUT



APPENDIX 5. PROGRAM FILES