# Low-cost intelligent educational laboratory temperature data acquisition and control device

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*Abstract*—A simple yet smart compact modular low-cost microcomputer input/output (I/O) laboratory appliance for signal converting and control of a temperature educational plant has been recently developed and assembled at the Faculty of Applied Informatics, Tomas Bata University in Zlín, Czech Republic. In this paper, the motivation for this design decision and the description of the unit and its parts together with full electronic schemes are presented. The development of the new unit has been motivated i.a. by the fact that the currently used converter device for teaching experiments does not meet elementary safety and contemporary educational standards requirements. The designed appliance preserves some crucial features of the old one, and simultaneously brings new useful functions; namely, it is equipped with a four-line LCD panel and buttons which allow calibration the I/O channels with saving, and with RS232 interface for serial communication with PC. The significant advantage of the device is its price which is much lower than for similar commercial products and makes the unit easily reachable. A particular example of using the appliance in the educational process is also provided to the reader. Unit imperfections and ideas of its possible future enhancement conclude the paper.

*Keywords*—Application, data acquisition, I/O converter, microcomputer, RS232, temperature control, thermal plant

## I. INTRODUCTION

TEMPERATURE measurement and control belongs among the most frequent tasks in automation and industrial process control practice [1]-[3]. Various sensors based on specific physical laws can be used for the measurement; such as, dilatational ones, sensors with an electrical property change, or those sensitive to the electromagnetic field etc. Widely used resistant thermometers are based on the correlation of the electrical resistance of the sensor material (platinum, nickel or copper) with temperature [4]. The change of the resistance must be then converted to an electrical (voltage or current) signal, e.g. by using the known Wheatstone bridge with the four-wire configuration [5].

Contrariwise, the plant temperature is to be controlled by

assorted technical means, e.g. by using electrical energy control tools such as a relay, triac, transistor etc. Both the functions, measurement and control one, together with a superior communication solution, can be realized via a single appliance – an I/O converter and control unit.

Due to relatively simple theoretical and practical aspects of temperature control and measurement and because of their above mentioned wide practical usability, these tasks are suitable in the educational process in automation and related subjects. About thirty years ago, a modular converter and control unit for students' laboratory exercises on heating (thermal) plant models was designed and developed at the Faculty of Technology, Technical University in Brno, Czech Republic. The unit stands as an interface between the controlled model and a control and computational part of the feedback (a personal computer – PC), and it provides the PC with unified measured signals from the plant and, contrariwise, transforms control signals into manipulated inputs that can drive the controlled plant.

The obsolete current appliance, however, suffers from some deficiencies which disable to keep using it for present and future modern control and identification teaching tasks. In particular, the unit appearance is unsightly, it is stricken by frequent failures and contains slackened parts and wiring which can harm students or teachers – moreover, original spare parts are almost impossible to be acquired nowadays.

In 2006, heating plants became property of the Faculty of Applied Informatics, Tomas Bata University in Zlín, Czech Republic. Because of the mentioned problems with current I/O converter and control units, we decided to develop a modernized, safe, compact yet modular, multichannel and adjustable converter/control device in order to provide students with a modern, low-cost, smart, easy-to-handle and extendable microcontroller unit that converts measured signal from the heating plant and drives the performance control input to the laboratory model. The modernized unit preserves some important properties of the current appliance; however, it does not suffer from mentioned deficiencies and its functionality is extended by a modern LCD panel, buttons for the SW calibration and the possibility to communicate with a PC via the RS232 interface.

The paper is organized as follows. The description of the laboratory heating control system with the current I/O converter and control unit is provided in Section II. Particular HW parts of the novel designed device are thoroughly introduced in Section III. Section IV is aimed to provide the

reader with the SW equipment of the new unit. A laboratory application control task, presented in Section V, verifies the usability and functionality of the microcontroller unit. A summary of the presented work along with suggestions of a possible future improvement of the designed appliance conclude the paper.

## II.  PRESENT STATE

The appearance and arrangement characterization of the current laboratory heating system is the objective of this section.

A sketch of the measurement and control system solution and functionality can be seen in Fig. 1. The central PC is equipped with Advantech PCI 1171 acquisition card, the interface of which is prolonged and terminated by an external ADAM-3968 wiring terminal board. The heating plant itself contains a small rheostat with a Pt100 sensor element. The rheostat is warmed up by 24V AC control input and connected to the converter/control unit by a double conductor wire. The heating plant also contains the main on/off switch, a heating body power driver, a heating element input signal and cooling selector, a cooling power driver, and a voltage presence signaling diode.

The I/O converter and control unit (see Fig. 2) powered by 230V AC from mains, which serves as an interface between the PC and the controlled plant, is equipped with two converter cards for signal processing from Pt100 sensors providing the normalized analog signal within the range of 0-10V DC.



Fig. 2 A photo of the current I/O converter and control unit – the front (up) and the back side (down)

Moreover it contains two AC control cards with binary pulse width modulated (PWM) TTL logic inputs, and a segment display.

Discrete-time measurement and control tasks are realized by the PC with WControl application [7] – an example of the project window, to which the user can insert several objects (such as controllers, reference input, display block, etc.), is pictured in Fig. 3. A teacher or student can select a template to the particular exercise task (on/off control with the penalization, standard proportional-sum-difference control, or a template with the generalized linear discrete-time controller), set controller parameters, and display and archive relevant data. This application serves only for execution of a simple task; alternatively, one can use e.g. the Matlab/Simulink environment [8] which, however, has to be equipped with the Real-Time Toolbox for processing signals from/to the acquisition card.



Fig. 1 Laboratory heating system scheme
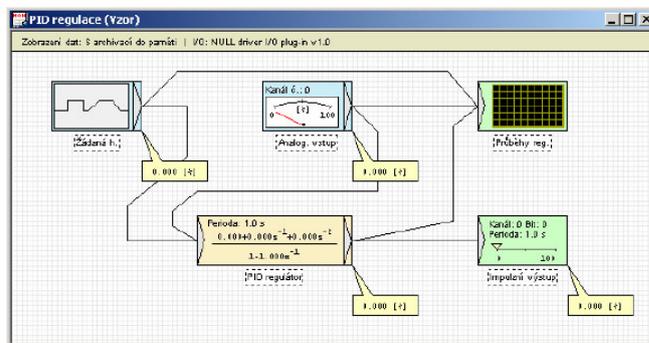


Fig. 3 WControl project window environment

## III. INNOVATED CONVERTER AND CONTROL UNIT HW DESIGN

As can be seen especially from Fig. 2, the current I/O converter and control is obsolete and it ought to be innovated. Therefore, we have designed and assembled a new device meeting basic requirements and standards on a modern control education appliance. Now, a sufficiently detailed description of particular HW parts of the modernized unit follows.

The new unit, the overall block scheme of which is provided in Fig. 4, adopts selected features of the current device and adds some new ones or improved others. It preserves two channels with analog measured data outputs and binary control action inputs – these features can be extended up to four channels.

Contrary to the contemporary state, the new unit is powered by the safe 24V AC input, the use of the microcontroller enables a more accurate measured data evaluation and the SW calibration via a simple keyboard - the settings can be saved to a memory. In addition, the unit can be connected with the PC by two independent serial RS232 interfaces and actual input and output data can be displayed on a four-line LCD panel.

Thus, let us further introduce every single component of the appliance.

### 1) Central Board

The central board means the part of the device that maintains the processing of control and data signals through the microprocessor. It is divided into two boards – the upper and the lower one – due to constructional and dimensional reasons.

The upper board (see Fig. 5) includes connectors for interconnection of particular components with the microprocessor MCF51AC128 with the core Coldfire® V1 by Freescale Semiconductor, Inc. [9]. These components are connected via MLW connectors for flat wiring to the control element. The board also contains a connector for the converter (data acquisition) cards with the analog 0-5V input for the microcontroller (pins PTB0-PTB3) and a connector for control boards with a timer FTM1 (pins PTF0-PTF3). The presence of the converter board at the corresponding channel is determined by means of pins PTB4-PTB7. The same function for control boards is provided by pins PTF4-PTF7 and PTC6. A connector for the LCD panel contains power supply and data pins at ports PTA0-PTA6. Close to the LCD display port, a potentiometer for adjusting the brightness of the display is placed. A 14-pin connector powered by 5V serves for the connection of the keyboard and for control of four LED diodes on pins PTD0-PTD4. The BDM (Background Debug Module) programmable interface is an inseparable part of the central board. PWM control signals (in TTL logic levels) generated by the Advantech card on a PC are fetched into K1 and K2 connectors and, subsequently, proceeded by the driver 74HC125 [10], optoelements PC827 and a flexible timer FTM1 in the input-capture mode on pins PTE2 and PTE3.

The lower part of the central board is connected with the upper one via the 9-pin Canon interface on COM1 and COM2.
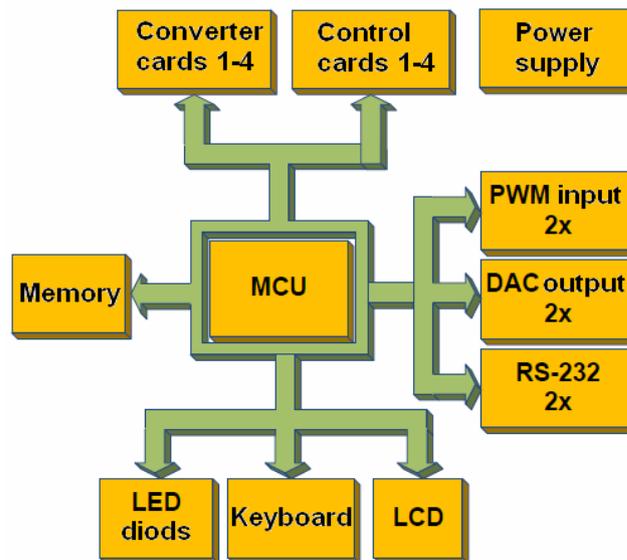


Fig. 4 New laboratory unit functional block scheme

In Fig. 6, a block scheme of the lower part of the central board is displayed. It integrates EEPROM 25LC256 memory of 256KB and two 12b DA converters MCP4821 [11], and its communication and connection with the upper board is realized via SPI interface at pins PTE5-PTE7. DA converter output protected by a Zener diode is then amplified to 0-10V by means of the operational amplifier LM358 and connected to the upper board by using K3 and K4 and to analog input of Advantech cards in the PC for the information about measured temperature. Both serial ports are placed on the board and adjusted by MAX232 integrated circuit for standard RS232 voltage levels. Note that the complete electronic scheme of the board is given in Fig. 7.

### 2) Keyboard

The keyboard of the size 3x3 placed at the front side of the appliance chassis and connected to the central board via a flat cable serves as a human-machine interface for the I/O converter and control unit. The keys provide moving to the left, right, up and down on the display, and can be used for confirmation or cancellation. The front panel also includes four green low-consumption channel-state indicating diodes.

### 3) LCD Display Board

The four-line display MC2004E-SYL [12] is joined with the central board via reduction to flat connector and it communicates with the processor by using of a 4-conductor bus. Its contrast an be adjusted by the trimmer located on the central board.

### 4) Converter Board

This board has been developed and designed for temperature measurement and conversion of the signal from Pt100 sensors in the 2-wire connection.
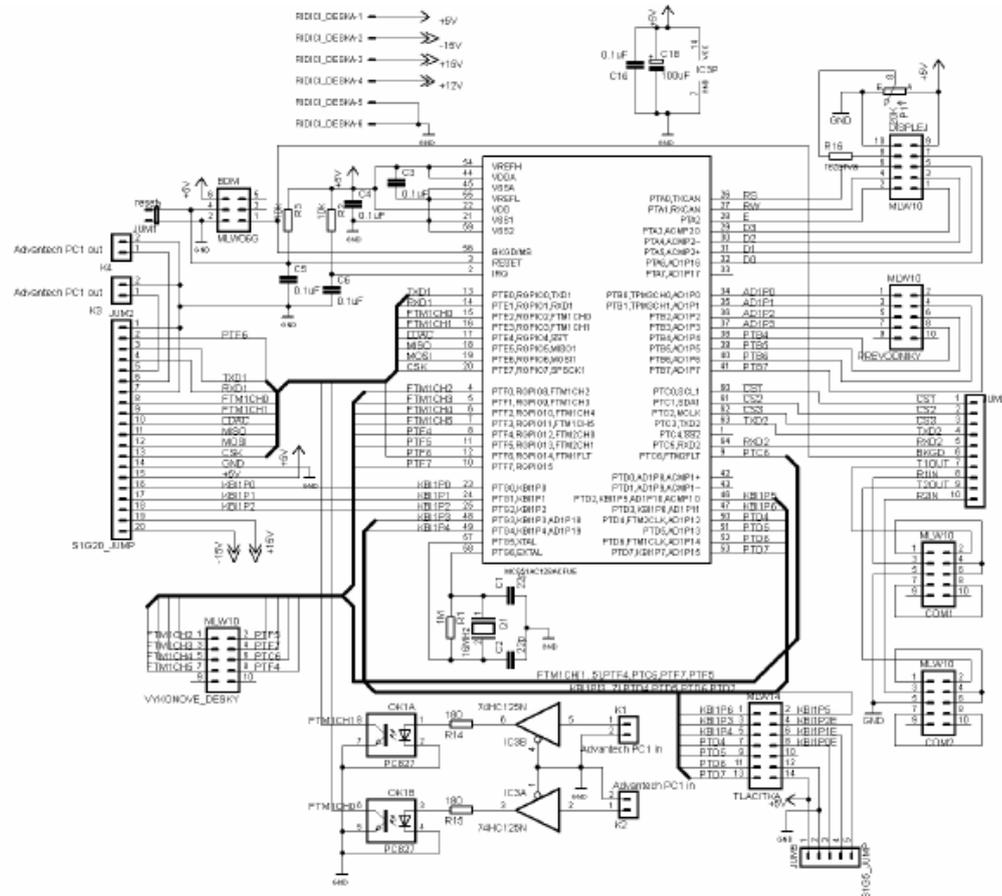
Fig. 5 Upper central board electronic circuit scheme
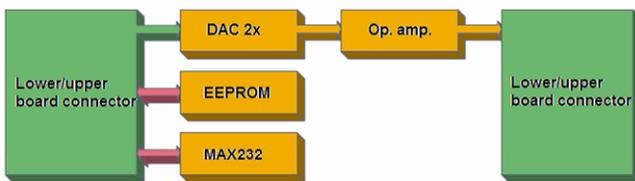


Fig. 6 Lower central board functional block scheme

It is based on the reference voltage TL431 powered by 12V with 2.5V output which is then fed the current reference with two operational amplifiers LM324. This reference current output enters a connector with the Pt100 sensor output. The voltage loss on sensors driven by the current reference signal is evaluated by a differential operational amplifier. This signal is then shifted down by the off-set of 100mV, amplified and trimmed to 0-5V by using two Shottky diodes. Finally, the output goes to a flat cable connector to the central board. The converter also includes jumpers to select the channel number. The measured temperature values are within the possible range of 0-300 °C. A functional block scheme of the board is given to the reader in Fig. 8 and the complete electronic scheme is displayed in Fig. 9.

### 5) Control Board

The full scheme of the control board can be seen in Fig. 10. PWM pulses of the period 1 s and the 8bit resolution generated by the microprocessor are sufficient for control of electric power driven into a heater inside the laboratory model. These pulses open a bipolar transistor BC337 [13] which is used due to the necessity to reduce the current load of the microcontroller output. This transistor then makes an opto-triac MOC3022 [14] switch on that ensures the galvanic isolation of the power part from the control one with the isolation voltage 7500V AC; subsequently, the optotriac output drives a power triac TIC226 [15]. The board is fed by the AC voltage from the power-supply by using the K1 whereas the hating body is connected via the K2 wiring terminal. It contains channel number selection jumpers as well.

### 6) Microcontroller

The above mentioned 32b microcontroller MCF51AC128 belong to the Flexis series which is compatible to 8b microcontrollers from this series. It is supplied by 5V DC and the maximum frequency reads 50.33 MHz with frequency of 25 MHz and includes i.a. a 128kB flash memory, 32kB RAM, a 20-channel 12b AD converter and three 16b counter/timers which can be configured as I/O PWM peripheries [9].
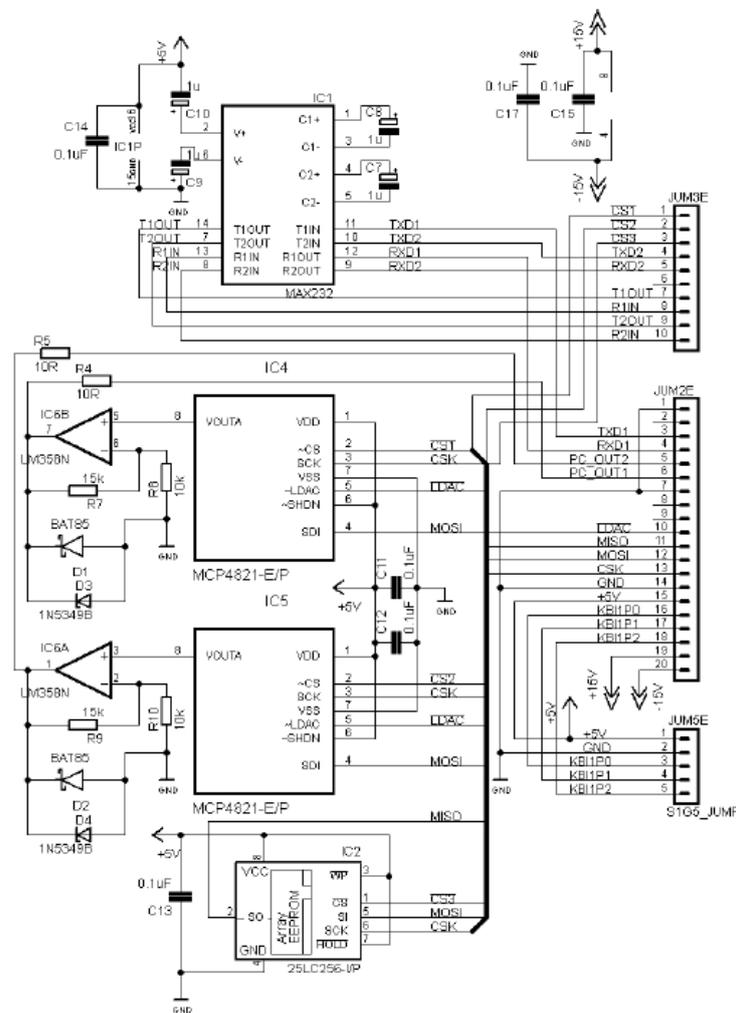
Fig. 7 Lower central board electronic circuit scheme

### 7) Power Supply

The apparatus is powered by 24V AC input with 4A power fuse. The input voltage is then branched and fed to control board as the power input and to rectifier GBU1002 [16]. The rectified voltage is then reduced by using two step-down controllers LM2576 to 12V and 5V DC with the maximum load current of 3A. By means of the DC-DC converter Tracopower TEN 15-2423 [17], the symmetrical +/- 15V DC voltage output with the maximum load current of 500mA is produced to supply operational amplifies of the converter board. All the outputs are accessible via three Molex connectors at the edge of the power supply board. A block and a complete electronic scheme of the power supply wiring are figured in Figs. 11 and 12, respectively.

### 8) I/O Converter and Control Unit Appearance

A 4-line alphanumerical display providing the user with currently measured and/or control data and a menu for the apparatus setting are located on the front panel of the device, see Fig. 13 for the photo. Navigational and setting buttons are placed right from the display. Four LEDs signalizing the connections of I/O boards are situated above the keyboard. On the back side of the unit, four blue Canon connectors for temperature sensors attachment are given. The smaller green terminal board serves for the connection of the heater element whereas the bigger one provides ±15V, 12V, 5V DC and GND voltage outputs. Data acquisition Advantech cards can be connected via white Cannon connectors and the black ones can be used for RS232 communication. On/off switch power button is placed on the left side of the appliance.
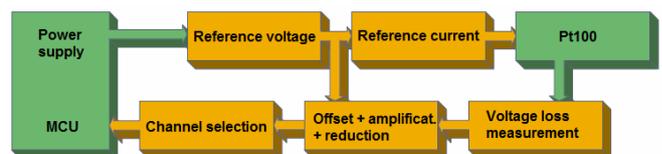


Fig. 8 Converter board functional block scheme
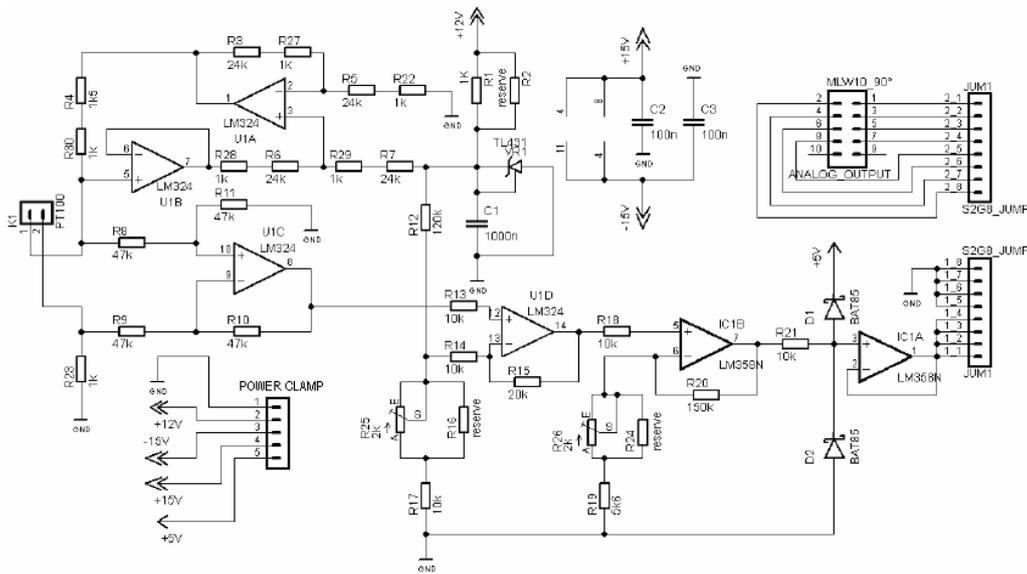
Fig. 9 Converter board electronic circuit scheme
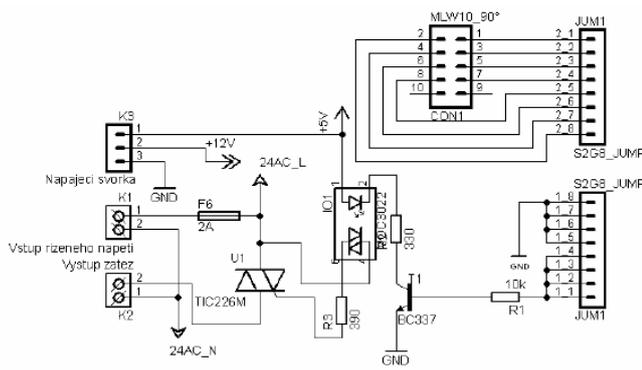


Fig. 10 Control board electronic circuit scheme
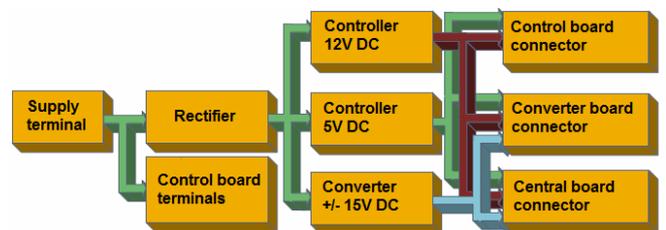


Fig. 11 Power supply functional block scheme
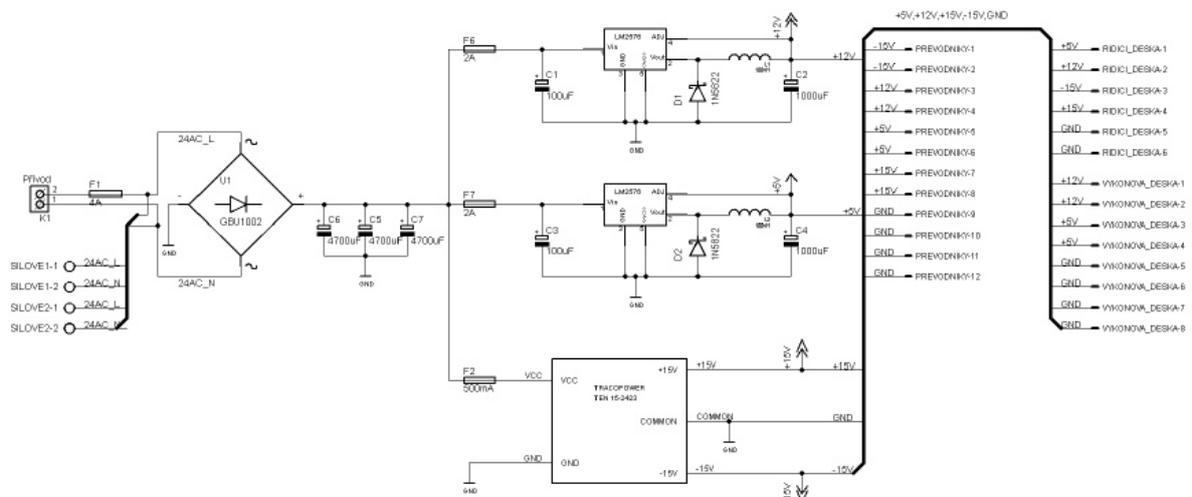


Fig. 12 Power supply electronic circuit scheme

Fig. 13 A photo of the designed I/O converter and control unit – the front (up) and the back side (down)

## IV. SW EQUIPMENT OF THE DESIGNED UNIT

Besides the description of the hardware equipment of the new device, a concise presentation of important parts and features of SW realization of the unit follows. The general programming code for the microcontroller was written in C language in Code Warrior ver. 10.3 environment based on Eclipse IDE [18] that integrates the Processor Expert utility which makes the work with and the setting of microprocessor peripheries easier. Separate programme blocks are described below.

### 1) General Programme

The programme source code is divided into three groups: The initialization sequence incorporating variables definition and peripheral setting is called for every single start or restart of the microcontroller. After that, the main programme is cyclically called, see Fig. 14.
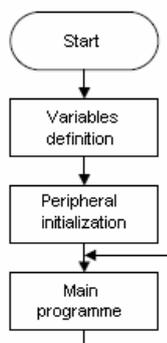


Fig. 14 General programme flowchart

### 2) Variables Definition and Peripheral Initialization

The variables definition block provides global variables (giving information about e.g. the present value of the control action, current temperature or the initial unit setting etc.) and functions definitions initialization.

The setting of microcontroller peripheries generating its own initialization function runs in the peripheral initialization block.

### 3) Main Programme

Before entering the cycle, the unit configuration is read in the main programme, and according to this data the device is set. Parallelly to the main programme, the keyboard interrupt (KBI) and interrupts from the serial link and binary PWM inputs can be processed, see Fig. 15 for the flowchart. Let us introduce particular blocks of the diagram.

#### a) I/O cards detection

Whenever an I/O card is plugged, it is detected and this information together with the channel number is saved and used in succeeding blocks.

#### b) Memory read and display layout

In this block, saved constants for the temperature calculation and serial communication settings are read from the EEPROM. The display layout is set according to the number of plugged I/O cards. For instance, if only two converter cards are plugged, then present temperature and manipulated input values are displayed for every single channel. Contrariwise, only temperature values are provided in case of all four cards, see Fig. 16.
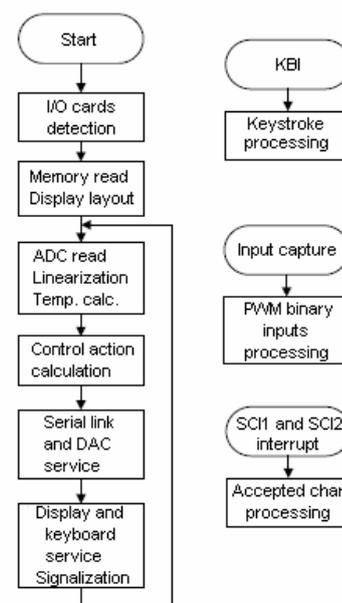


Fig. 15 Main programme flowchart

```
┌──────────────────────────────────┐
│ C h a n n e l : 1 | | C h a n n e l : 2 │
│ T : 0 0 0 . 0 ° C | | T : 0 0 0 . 0 ° C │
│ C h a n n e l : 3 | | C h a n n e l : 4 │
│ T : 0 0 0 . 0 ° C | | T : 0 0 0 . 0 ° C │
└──────────────────────────────────┘
┌──────────────────────────────────┐
│ C h a n n e l : 1 | | C h a n n e l : 2 │
│ T : 0 0 0 . 0 ° C | | T : 0 0 0 . 0 ° C │
│ O u t p u t :   1 | | O u t p u t :   2 │
│ P W M :   0 0 0 % | | P W M :   0 0 0 % │
└──────────────────────────────────┘
```
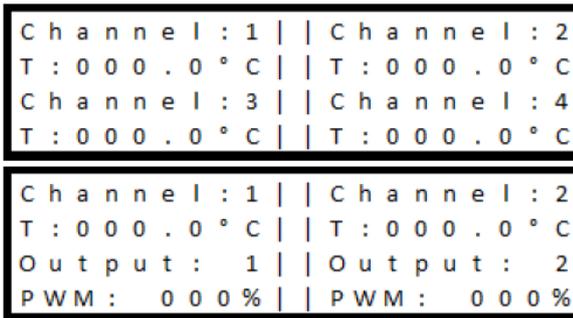
Fig. 16 Display layout for four (up) and two (down) plugged cards

### c)    AD converter data read and temperature calculation

Starting of A/D conversion is performed every single cycle, the data are filtered and, subsequently, the arithmetical means temperature values are evaluated for each channel.

A platinum resistance thermometer is characterized by a high resistivity ($\rho \approx 0.1 \mu\Omega \cdot m$ at 20 °C), a long-term stability and accuracy; platinum has high melting point (1769 °C) and it is chemically resistant [4], [5], [19]. Therefore, it is suitable for the measurement of relatively high temperature in many industrial processes and applications. In the described hating system, Pt100 thermometer with the normalized resistance of $R_0 = 100\Omega$ at 0 °C is used. For the range of temperatures from 0 °C to 850 °C it approximately holds

$$R = R_0 \left(1 + At + Bt^2\right) \tag{1}$$

where $A = 3{,}9083 \cdot 10^{-3}\,°C^{-1}$, $B = -5{,}77 \cdot 10^{-7}\,°C^{-2}$ [19]. Since the value of the quadratic coefficient is relative low, it can be neglected for many real applications in which the exact temperature value is not necessary to be acquired. Hence, it one may write

$$t \approx \left(R / R_0 - 1\right)/ A \tag{2}$$

which has been implemented in the designed unit.

### d)    Control action calculation

Whenever the serial communication is active, the received control value from SCI1 and SCI2 interrupts is converted and then the control action in the form of a PWM pulse is generated. The PWM timer resolution reads 8 bits and the period is defaultly set as 1 s which is satisfactory for this reason since one half-period lasts 10 ms (at 50 Hz).

Binary inputs from the PC (Advantech cards) are received by FTM1 timers with the input capture function by which lengths of input logical levels are measured. An interrupts is generated whenever the logical level is changed and, subsequently, the logical value is detected and copied to microprocessor output for the control board processing. The ratio of particular logical values lengths is measured and, afterwards, provided as a PWM value on the display.

### e)    Serial link service and DA conversion

For serial communication, the actual temperature value at each channel is send to the serial link in every single cycle of the main programme. The value can be within the range $[0.0, 999.9]$. Analogously, a received value of the required control action must satisfy the same range and it can be sent to PWM generator only if it has been changed; hence, it is not necessary to use a continual PWM value transmitting.

DA converters send the measured value to the output irrespective of the serial link activity.

### f)    Display and keyboard service and signalization

The display service provides functions for screening of the current temperature and/or PWM value, or the settings menu for the unit. Keystrokes of buttons on the keyboard taking care of moving on the display (←, ↑, →, ↓), confirmation (OK), cancellation or return in the menu (ESC), channel parameters settings changes, PWM setting and calibration for temperature evaluation are captured by using KBI interrupt. The microcontroller drives four LEDs on the front panel of the chassis that signalize the presence of converter and control boards. When controlling the channel via the binary input, one diode signalizes the current state of the input.

### 4)    Serial Communication

### a)    Communication parameters

As mentioned above, the unit is equipped with two independent RS232 ports. It is necessary to set RS232 parameters properly prior to the serial communication starts for its flawless functioning. The correct setting for the converter/control board is the following:

Parity: none
Word length (data bits): 8 bit
Number of stop bits: 1
Baud rate: 9600 Bd
Flow control: off
Terminator string: CR

The communication between the converter/control unit and the PC is made in ACSII characters. Accepted string giving information about the desired control action must be of the pattern *annn\r* where *nnn* is the decimal value of the control signal and the terminator *\r* means a jump to a new line. The value can be accepted regardless of in what phase the program is. The string sent to a PC and containing information of measured temperature has the format: *nnn.n\r* where the sequence *nnn.n* means the temperature value. In contrast to input control signal, the measured output values have to be performed every single cycle of the main programme.

### b)    The use of Matlab/Simulink

Communication parameters are to be set after linking cable connection using the function `serial()` as

```
s = serial('COM8', 'BaudRate', 9600,
'Terminator', 'CR' );
```

where COM8 stands for the port to which the device is connected.

The setting can be checked and displayed by the command `get(s)`. One the parameters are set, the communication channel is to be open by using `fopen(s)`, whereas `fclose(s)` terminates the communication or makes the channel free. For the receiving of values from the unit, the command `fgets(s)` can be written in an m-file. In the contrary, function `fprintf()` sends the control action value to the unit. For instance, the command

```
fprintf(s,'a050')
```

means the desired manipulated input equal to 50 %.

The use of Simulink requires the same setting made from the command line (or m-file) as described above. Blocks *To Instrument* and *Query Instrument* proved to be suitable for the communication with the I/O converter and control unit. In both the blocks, ASCII code must be set as the data format, and the string format reads *a%3d* and *%f* for the former and the latter block, respectively.

## V. EXAMPLE

The main objective of this session is to practically verify the functionality of the designed device on a selected laboratory student control task; namely, the application of the dynamic inversion tuning method (or equivalently, the desired model method) [20].

As soon as the power supply of 24V AC is plugged, the device configuration is being loaded, that is displayed in the LCD panel as well as indicated by diodes. If at least one pair of I/O cards is plugged, it is possible to set the gain and offset of the input signal generated by the converter board via keyboard buttons for the temperature evaluation (see Fig. 17); the calibration setting can be saved.

Hence, let the particular heating plant be described by modeled by the second order system with the transfer function

$$G(s) = \frac{1.37}{(86s + 1)(12.7s + 1)} \tag{3}$$

the parameters of which have been obtained via an identification procedure made by means of the current (old) converter and control unit.

According to the dynamics of model (3), set the sampling period as $T_S = 20$ s. As first, calculate the equivalent discrete-time plant model with this period giving rise to the Z-transform transfer function

$$G(z) = \frac{0.145z^{-1} + 0.08z^{-2}}{1 - z^{-1} + 0.164z^{-2}} \tag{4}$$

Now consider a linear discrete proportional-sum-difference

controller and choose the desired output temperature time constant as $T_W = 70$ s. The methodology introduced in [20] results in the following controller

$$C_{PSD}(z) = \frac{1.105 - 1.104z^{-1} + 0.182z^{-2}}{1 - z^{-1}} \tag{5}$$

The comparison of measured control responses with those obtained via the Matlab/Simulink simulation is displayed in Fig. 18 where $u(t)$ means the control action, $w(t)$ stands for the reference signal and $y(t)$ represents the output temperature value.

As the second test, let a proportional-sum control law be taken into account. Prior to the controller parameters determination, the model has to be reduced to the first order plus dead time one e.g. as

$$\hat{G}(s) = \frac{1.37}{86s + 1}\exp(-12.7s) \tag{6}$$

Choose the desired maximum output temperature as 20 %, which yields the maximum possible integer sampling period of $T_S = 4$ s and the following eventual controller transfer function

$$C_{PS}(z) = \frac{3.016 - 2.879z^{-1}}{1 - z^{-1}} \tag{7}$$

Again, real measured and simulated output data are compared in Fig. 19.

The example results give a very good closeness of ideal (simulated) and real (measured) control responses, and the functionality and usability of the I/O converter and control unit are clearly verified. Note that the selected decimal accuracy of measured temperature with the 12b AD converter give sufficiently smooth values and, similarly, the PWM setting does not inflict fast abrupt changes of the control action (except for rapid changes of the reference signal).

```
Calib.ADC:>Channel   1
            Channel   2
            Channel   3
            Channel   4

Channel   1:
>R_Gain:        +000.000
 R_Offset:      +000.000
 Default
```
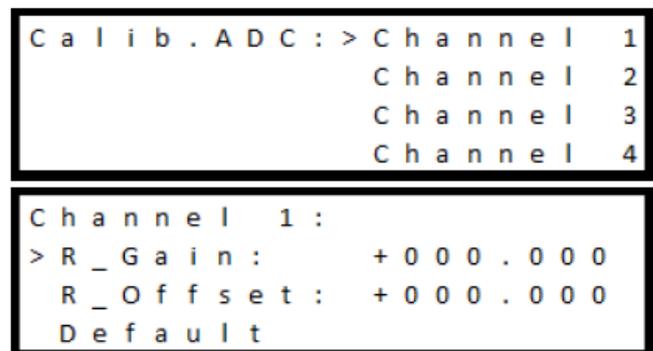
Fig. 17 Display of AD converted signal calibration
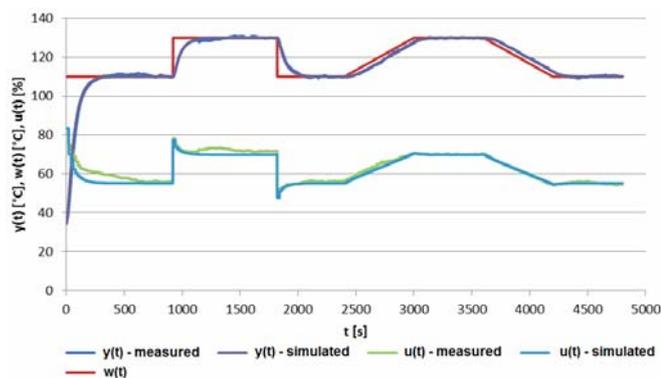
Fig. 18 Control responses for plant (3) with controller (5)
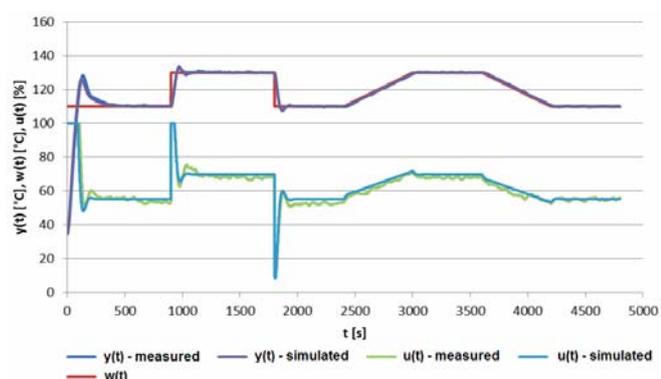


Fig. 19 Control responses for plant (3) with controller (7)

## VI. DISCUSSION AND CONCLUSION

Because of the obsoleteness of a currently used laboratory converter and control unit for heating plants, a modernized device has been designed and assembled for educational purposes in automation. In this paper, a sufficiently detailed description of the appearance and functionality of the new have been presented. It is currently a prototype yet the functionality of the apparatus has been tested and verified. This innovation brings the preservation of basic functional properties of the obsolete appliance, and improves many other attributes; namely, the unit is equipped with a LCD display, a keyboard and the RS232 interface, it is compact, intelligent and safe and can be easily modularly extended. The crucial benefit is the expanse of components and manufacturing on the designed device – the total cost is about 350$. The deficiency of the device rests mainly in the temperature measurement accuracy and noise that should be removed by a revision of transfer cards equipped with RC filter on the output.

There are, however, still many features that might be improved in a future version. For instance, temperature measurement can be allowed to other sensors besides Pt100, e.g. to thermocouples. Or, the unit would process a general unified electrical signal, such as 0-10 V DC, which may help to extend the area of its applicability. Present low prizes of some electronic components also enable to utilize more modern parts, namely, a touch LCD panel. Since many present-day products can be remotely monitored and/or controlled, we plan to equip the unit with web server and the possibility to make remote laboratory experiments. Last but not least the designed boards can be more compact and independent to each other in the future.

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