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Abstract - The paper describes a digital PID controller realized in the framework of a student project at the Department of Automatic Control and Electronics of Faculty of Electrical Engineering in Sarajevo. This project included the complete solution, from hardware design to software implementation of control algorithms.

Digital PID controller was implemented which was based on a microcontroller Microchip PIC16F877A. The device has the possibility of adjusting the value of PID controller parameters, with their display on the LCD display.

Possibilities that the value of control error could be passed as an input signal on the analog input of the controller, or that the control error value might be formed internally in the controller itself were considered in advance. In this case, it was ensured that default value was either brought from outside through the analog input, or generated internally (with the possibility of setting the default value). PWM was used for output of the PID controller. Device is capable for proper connecting to the RS-485 bus. Realized controller has found great use in the teaching process.

I. INTRODUCTION

While managing industrial processes, in over 90% cases, industrial PID controllers are used, as stated in [1]. They are often referred to as standard controllers. PID name comes from the acronym for the proportional, integral and derivative component control activities, which are formed based on signal error. Prevalence of this class of controllers stems from their simplicity in linear systems control, and also from proven robustness of control laws in many important applications. On the other hand, the simplicity of these controllers can also represent their weakness, because there are controlled objects (objects with significant nonlinearity), which require the application of complex control laws in order to achieve satisfactory performance. These controllers are also used in the control of objects in motion (at the rate and trajectory) in which stability and precise tracking of referent value are required. As noted in [2], autopilots, which are most frequent in airplanes and boats, and other moving objects, are actually PID controllers. Therefore, even today a lot of attention is paid on implementation and setting parameters of the PID controllers. Another reason is the fact that most nonlinear systems can be approximated with linear in vicinity of the operating point.

There are analog and digital PID controllers existent today, but the latter is mostly applied, and it is based on discrete equation of the controller. Reasons for this are multiple advantages of digital compared to analog controllers. Some of these advantages are high accuracy, adaptability to new requirements by simply changing the programming code, the possibility of removing negative actions of measurement noise by sampling and the fact that price does not increase rapidly with the increasing complexity of the management system, as is the case with analog controllers.

This paper describes implementation of digital PID controller, realized in the framework of student work in Electrical Engineering Faculty in Sarajevo. The controller had to meet the following requirements:

- implementation based on PIC16F877A microcontroller,
- possibility of adjusting the value of PID controller parameters, with their view on the 7-segment display,
- the possibility that the control error could be led to analog input of the controller, or that the value of this error is formed internally in the controller itself,
- output of PID controller presented in the form of PWM signal,
- provided ability of connection establishment to the RS-485 bus.

This paper is structured as follows. In section II the data analysis of the problem of realization of the controller in accordance with the requirements specified that this controller had to meet are given. In section III a form of mathematical algorithms that was realized is provided. Section IV provides brief notes on the hardware components used. Section V gives an overview on the implemented program code. View on the complete system which represents a digital PID controller with supporting hardware is given in Section VI. Finally, section VII provides the testing results.

II. PROBLEM ANALYSIS

By analyzing the problem of realization of a digital PID controller conclusion is that it can be divided into several interconnected units. To facilitate understanding of the problem, a brief description of each of these parts is provided.

The central part of the implementation is the mathematical algorithm of the controller. Also, the additional components which would complete the functionality of the realized device are absolutely needed.

The device has the possibility to adjust the value of PID controller parameters, with them being displayed on the LCD display. Setting the values of the parameters is enabled using the rotary switch, which is connected to the LCD display on which adjusted parameters values are constantly displayed. By turning a rotary switch to one or the other side, the currently selected parameter value increases or decreases. Selection of parameters to be adjusted is done by pressing a rotary switch. The set value of each parameter is memorized until its next adjustment or change.

PID controller has three mode regimes. In the first mode (type 0) measured and the reference value are brought to the two analog inputs from the outside and control error is formed internally in the controller. The second mode (type 1) means that the control error is brought directly to the analog input of the controller. In the third mode (type 2) control error is formed internally in the controller, based on the measured value brought to the analog input and reference value entered as a constant over the rotary switch. In case that any value is brought from outside to the analog input A/D conversion of that value is provided. This is done via software control.

Output from controller is actually a PWM signal. This means that the controller provides a digital output signal presented via impulses with different lengths of the logical levels. By changing relation between the duration of the logical "1" and logical "0" the mean value of the output signal is changed. Logical "1" is represented with a voltage of 5 (V), and logical "0" with 0 (V). A fixed period of the PWM signal 1 (ms) is then taken, while only the duration relation between the logical levels is changed.

Hardware-wise, the device carries a possibility of establishing connection to the RS-485 bus, but it is not realized with any software.

III. ALGORITHM DESCRIPTION

Algorithm of digital PID controller functioning can be obtained with discretization of the equation that describes analog PID controller, which is given in detail in [3].

The basic equation that describes the effect of analogue PID controller is:

$$u(t) = K\left[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right]. \tag{1}$$

In the equation (1) $e(t)$ is control error signal, and $u(t)$ is controller's output signal. Controller's gain is K, its integral and derivative time constants are T_i and T_d, respectively.

The simplest way of discretization of analogue PID controller is to transform the above equation in difference equation. Recursive method is used, in which the control at the time kT is calculated on the basis of the control in previous moment, and control growth:

$$u(kT) = [u(k-1)T] + \Delta u(kT) \tag{2}$$

Control growth $\Delta u(kT)$ can be expressed as:

$$\begin{aligned}\Delta u(kT) = Ke\Big\{&(kT) - e[(k-1)T] + \frac{T}{T_i}e(kT)\\ &+ \frac{T_d}{T}\big[e(kT) - 2e[(k-1)T] + e[(k-2)T]\big]\Big\}\end{aligned} \tag{3}$$

Equations (2) and (3) represent a discrete PID controller functioning algorithm whose input is the value of control error, and they are used in the software implementation of the controller based on microcontroller PIC16F877A.

IV. USED HARDWARE COMPONENTS

In the project PIC16F877A microcontroller was used, and its pin placement diagram is given in Fig. 1a. Microcontroller has 40 pins, and for project 31 pins are used. Two pins served as analog inputs, and 15 pins as digital inputs/outputs. Also one pin was used to generate PWM signals, and three pins were used for RS485 communication.

Rotary switch, Fig. 1b., is an electronic device that is used for parameter adjustment. Its working principle is basically very simple. Two operations that can be performed on this device are turning in both directions, and pressing the switch itself. Microcontroller is connected to the three outputs of rotary switch. All three outputs provide a digital output signal, a logical "0" or logical "1". Two ports which represent the two phases change their status by turning one step. Counting these steps, based on the number of changes of signal, adjusts the parameters. The order of signal changes of the two phases is crucial for detection of the direction. The third output gives the pulse with positive and negative edge at each pressing of the switch. It is used to generate external interrupt. Pressing the rotary switch generates cross from adjusting the first parameter to setting another parameter of the controller, in the adjustment controller mode, while in the controller work mode, switch only adjusts the reference voltage.

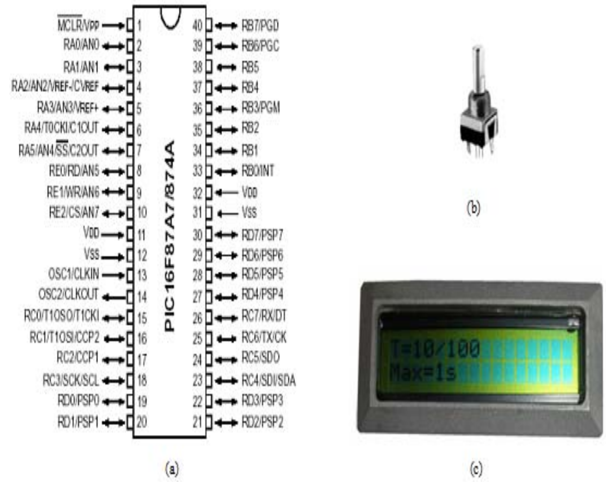


Fig. 1. Pin placement of the microcontroller (a), rotary switch (b), LCD display (c).

On the LCD display, Fig. 1c., the value of the parameter that is currently being adjusted is displayed. Information on display is sent in digital signal form from the microcontroller, print on the display is controlled the same way.

In addition to these three main components, connector for programming, switches for selecting mode, and some more minor components, whose use is very simple, and shall not be explained in detail in this paper, are used.

V. PROGRAMING CODE OF MICROCONTROLLER

After making the hardware, next logical step was to program the circuit itself. The code is written in CCSC Compiler, version 4, from manufacturer Custom Computer Services Inc. More information about this manufacturer and the compiler can be found in [4]. Mathematical algorithm of the controller before mentioned is implemented in the code, and also parts of the code necessary for the proper functioning of other hardware components. Schematic view of the written software is given in Fig. 2.

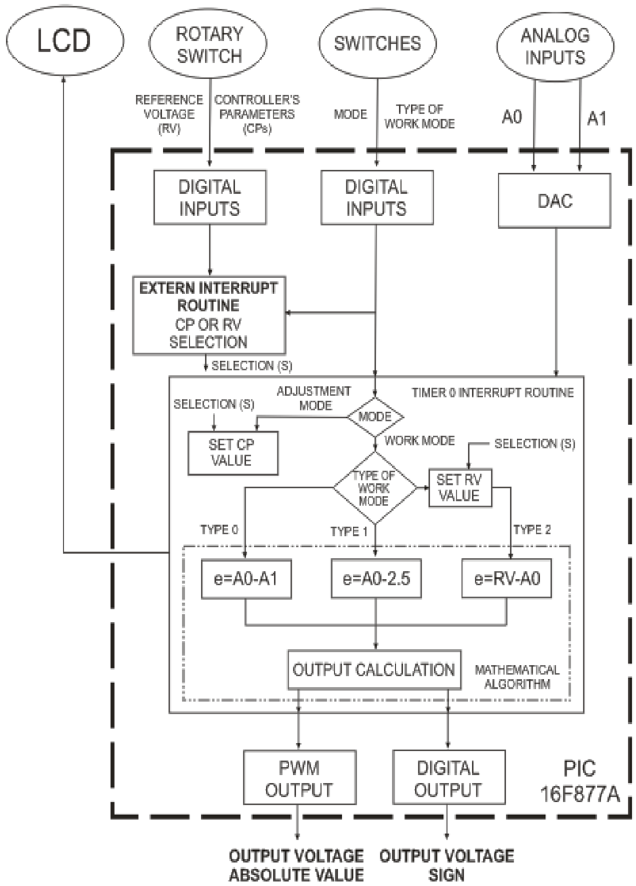


Fig. 2. Schematic display of the software.

The structure of the software is visible on the figure. Software reads the values of the required analog inputs (A0 and A1), the status of control switches, and the condition of a rotary switch. Both analog inputs have range 0-5 (V). Control switches are used for choosing between work, and adjustment controller mode, also for choosing the type of work mode. Rotary switch has a dual role. It can set controller's parameters (CPs – Controller's Parameters) in adjustment mode, or reference voltage (RV), in work mode. Simple press the switch performs parameter selection, which shall further be adjusted. Choice of parameters is processed in the interrupt routine of external interrupt and is determined by the output of the routine marked with S in Fig. 2. The value of the parameter currently being adjusted can be seen on the LCD display.

Timer 0 is used to define any time period. In his interrupt overflow routine, which performs approximately every 3.2 (ms), mathematical algorithm for calculation and generation of the output voltage is called. Mathematical algorithm is called with every k-th iteration of interrupt execution routine, where k stands for quotient of time of sampling versus time-overflow of timer 0. Also, every 100 (ms) LCD display is refreshed to update the new values, where if the controller is in adjustment mode, its parameter values are displayed, and its reference voltage is displayed if the controller is in work mode. With each execution of interrupt routine, timer 0 reads the state of the rotary switch and then registers changes in the values of adjustable parameters.

Method of calculating control error (e) depends on the type of work mode, which is coded by switches. In the event that the control error is brought directly to the controller, as in type 1, the analog input range is scaled from 0-5 (V) to –2.5-2.5 (V) by using the aforementioned software. This has to be done so that the controller can work with error of arbitrary sign.

Mathematical algorithm calculates the output voltage and then sends its absolute value on the PWM output port, and sign on the digital output.

VI. REALIZED SYSTEM

Functional scheme of the realized system is given in the Fig. 3.

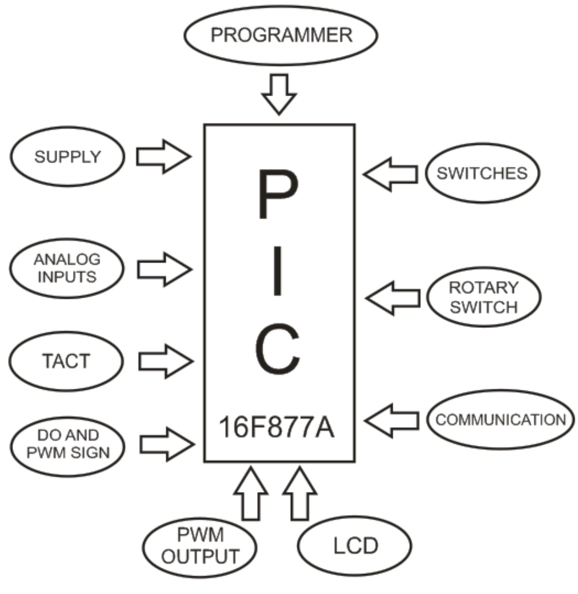


Fig. 3. Functional scheme of the realized system.

The device is a product of fully independent student work. Production implied the implementation of the entire hardware circuit, and construction of work algorithm. The paper used 17% of the total 368 bytes of RAM and 38% of 8K 14-bit words of ROM memory of the used microcontroller.

First it was necessary to make the electrical scheme. The scheme was made in the Altium Designer software package, version 6, from the manufacturer Altium Limited, and more information on the manufacturer and the software package can be found at webpage [5]. Based on it a PCB scheme for construction of the 10×12 (cm) tile. Printed tile with designated parts of the data is given in Fig. 4. Entire hardware circuit is given in Fig. 5.

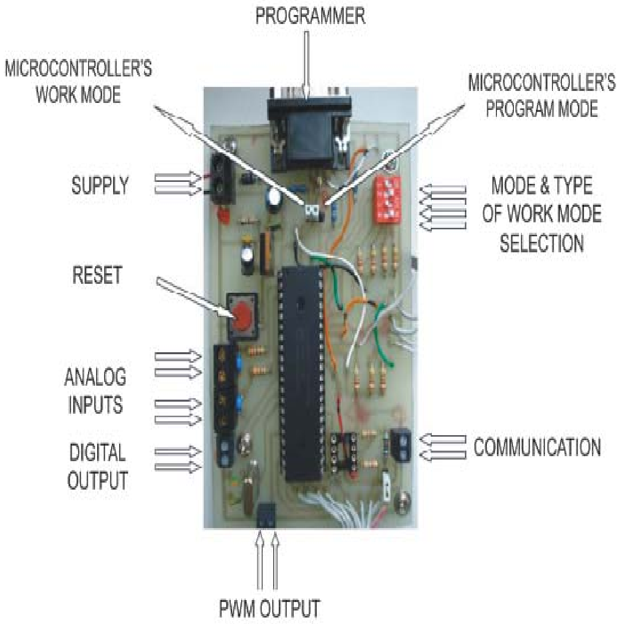


Fig. 4. Realized system.

Fig. 5. Digital PID controller.

Controller calculates the output voltage and generates the output by using PWM signal based on the value of control error that was either lead directly to the analog input, or formed internally in the controller. Output from the microcontroller is previously mentioned PWM signal. Since the PWM output is defined only to show a positive output voltage, PWM signal in fact represents the absolute value of the voltage and its sign appears in the appropriate digital output. Based on the sign and absolute value of the output voltage it is possible to reconstruct the real value of output voltage by using additional electronic circuits. This form of output voltage could be used for example in motor control, where the sign is used to control direction, and the absolute value for determining the speed.

Controller's parameters can be changed at any time, with them being display on the LCD display. All parameters are set as a percentage of the maximum value, which can easily be altered within the code. Gain K and integral time constant T_i are both set from 1 to 100% of the maximum value with step of 1%, while the maximum value of gain is 10, and of time constant 100 (s). Derivative time constant T_d can be set from 0 to 100% of the maximum value, with step of 1%, while its maximum value is 10 (s). Sampling time T is adjusted from 10% to 100% with step of 10% and the maximum value is 1 (s).

Rotary switch can also be used for adjustment of referent input voltage in the controller, in one of work modes. In this case, the voltage is adjusted from 0 to 100% of the maximum value, with step of 1% and the maximum value being 5 (V).

Switches are used for selection between work and adjustment controller mode, and for choice of type of work mode. Type of work mode defines the way of calculating control error.

The choice of sampling time is very important in digital systems. Empirical rules that apply to its selection are explained in more detail in [3]. Practically upper limits on the values of sampling times are set, while the lower limit in the ideal case should be zero. In this project sampling time is taken from the range from 0.1 (s) to 1 (s), which is appropriate for the controlling of slower technological processes, such as level control and flow control. It is important that the lower limit the range of sampling time is greater than the time needed for mathematical algorithm of controller to finish. When the execution time of program is calculated based on number of assembler instructions and microcontroller's tact it is less than 0.0030 (s) provided that all instructions execute in two cycles, and all of them are executed once. This second assumption is of course not true for all instructions, but this time is much less than 0.1 (s) which justifies the minimum sampling time.

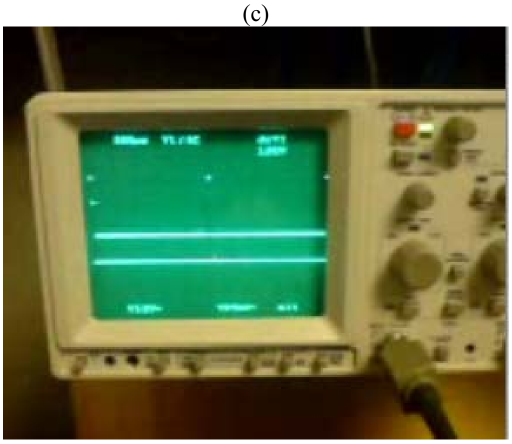
VII. Testing Results

The accuracy control of the realized system was performed by recording PWM controller output when its input changes. The results obtained are shown in Fig. 6.

(a)

(b)

(c)



(d)

Fig. 6. Measurement results.

Testing of controller is carried out by leading adjustable value of control error to its analog input. Parameter values for the results shown in Figure 6 are: $K = 0.2$ $T_i = 100$ (s), $T_d = 0.1$ (s), T = 0.1 (s).

Fig. 6a. shows the PWM output when the control error value was 1.25 (V), while Fig. 6c. shows the output with a negative value of –1.25 (V). Fig. 6b. shows the output when the error value is 2.5 (V). In Fig. 6d. error had zero value.

In this test, proportional and integral components of controller came to fore, given that the error did not change.

Testing results which are shown here are not the only ones that came from usage of this controller, since numerous other testing methods on this controller were carried out.

VIII. CONCLUSION

This paper describes the implementation of a digital PID controller. Controller is based on PIC16F877A microcontroller. Microcontroller is the "brain" of the device, given that it performs mathematical algorithm of PID controller. The device includes additional hardware components necessary for its adjustment and use in practice. Implementation procedures of this study followed the ones used to create a PID controller which is applied for controlling of real technological processes. In order to realize this project, the authors used previously acquired knowledge from the theory of digital control systems and knowledge acquired in construction of microcontroller based electronic circuits. In this way ideal synthesis of this knowledge was enabled, thus paving the way for their exploitation for production of circuit applicable in practice.

Controller itself has been successfully applied to laboratory exercises on subjects dealing with the automatic control.

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