AUTO-TUNING MULTI-LOOP DIGITAL PID CONTROLLER USING PSoC5LP

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ABSTRACT

This paper presents the design and implementation of a multi-loop digital PID controller that operates with different types of variables, allowing centralizing the processes in a smaller number of devices offering better management of them. In addition to having manual tuning, the digital device includes an independent auto-tuning mode for each loop, which allows it to be affordable to a greater number of users, all this making use of a PSoC5LP.

Keywords: automation, auto-tuning, multi-loop, PID, PSoC5LP.

1. INTRODUCTION

Even with the rapid evolution in control hardware, the Proportional-Integral-Derivative (PID) controller is still the most widely used in industries where processes are controlled. The Proportional action adjusts the controller output according to the size of the error. Integral action can eliminate steady-state offset and future trend is predicted through Derivative action.

There is a wide variety of structures in the PI controllers and in general in the PID controllers that have been proposed throughout history. As [1] suggests, an important reason for the non-standardized structures is due to the transition from pneumatically operated controllers to electronic implementation and now to microprocessor implementation.

Usually, functional blocks and sequential algorithms are combined with PID controllers. Many regulatory control strategies, followers, start and stop, can be designed around a classical PID controller. This provides the basic means for good regulatory control, smooth transitions and fast start/stop.

In the process industries, more than 97% of the regulators are of the PID type. Most of the loops are actually under PI control. More than 60 years after the Ziegler-Nichols publication on tuning, and with the numerous articles published on tuning methods, it seems that the use of PID controllers has already met expectations [2].

Surveys indicate that the PID controller is the main controller in the process industries. After many years of experience, the control loops, often considered too simple, do not work as well as could be expected. The failure comes from the lack of knowledge needed to maintain the control loops, to tune the controllers, to design suitable processes for control and to design a suitable control configuration for a given process. Poor performance control can have many different causes. However, obtaining good tuning always leads to better cost-benefit ratios.

2. THE PID

The textbook version of the PID controller is generally given in the form [3], [4]:

$$u(t) = K_p\left[e(t) + \frac{1}{T_I}\int_0^t e(\tau)d\tau + T_D\frac{de(t)}{dt}\right] \quad (1)$$

Or in the form:

$$u(t) = r_0 e(t) + r_{-1}\int_0^t e(\tau)d\tau + r_1\frac{de(t)}{dt} \quad (2)$$

Where:

$$e(t) = w(t) - y(t) \quad (3)$$

And the relationship between the equations is given by (4).

$$K_p = r_0 T_I = \frac{K_p}{r_{-1}} T_D = \frac{r_1}{K_p} \quad (4)$$

Where $u(t)$ is the controller output, $y(t)$ denotes the process output, $e(t)$ is the error and $w(t)$ is the reference signal or set point. The controller parameters are defined as follows: K_P proportional gain, T_I integral time constant and T_D derivative time constant.

Using the Laplace transform, it is possible to convert the PID controller equation to the form:

$$U(s) = K_p\left[1 + \frac{1}{T_I S} + T_D S\right]E(s) \quad (5)$$

Where s represents the Laplace transformer operator. From (5) it is possible to obtain (6) which corresponds to the transfer function of the PID controller.

$$G_R(s) = \frac{U(s)}{E(s)} = K_p\left[1 + \frac{1}{T_I S} + T_D S\right] \quad (6)$$

To obtain a digital version of the continuous-time PID controller it is required to discretize the integral and derivative components of the equation. When the T_0 sampling period is small and the noise of the process output signal is effectively filtered out, the simplest algorithm is obtained by replacing the derivative with a first-order difference.

$$\frac{de}{dt} \approx \frac{e(k) - e(k-1)}{T_0} = \frac{\Delta e(k)}{T_0} \quad (7)$$

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Where *e(k)* is the value of the error at the time k of sampling, i.e. at time $t = k*T_0$. The easiest way to approximate the integral is by simple addition so that the function is approximated in continuous time by steps of duration T_0. If the continuous-time signal is discretized using the backward step function, rectangular method (BRM), this is obtained (8).

$$\int_0^t e(\tau)d\tau \approx T_0 \sum_{i=1}^{k} e(i) \tag{8}$$

Thus the most commonly used equation in the formal description of a digital PID controller is (9).

$$u(k) = K_p \left\{ e(k) + \frac{T_0}{T_I} \sum_{i=1}^{k} e(i) + \frac{T_D}{T_0} [e(k) - e(k-1)] \right\} \tag{9}$$

Because the total value of *u(k)*controller output is usually calculated in terms of the current plant position, this type of algorithm is also known as an absolute or position algorithm for PID controllers. This type of algorithm is also known as a non-recurring algorithm, where all previous error values $e(k - i)$, $i = 1, 2, \dots k$ must be known, to calculate the integral contribution and thus the action of the controller [5]. In real industrial applications, this is not possible to a large extent because it would be necessary to keep all the above error values in the memory of the control computer.

Recurring algorithms are therefore more suitable for practical use. Both the integral contribution alone and the entire controller output can be calculated regularly. Instead of a position algorithm, it is possible to use a component control algorithm, where the controller output is determined by the sum of the individual components and only the last value of the integral component is retained in memory. In this case, the algorithm obtained takes the form of (10).

$$u(k) = u_P(k) + u_I(k) + u_D(k) \tag{10}$$

Where:

$$u_P(k) = K_P e(k)$$
$$u_I(k) = K_P \frac{T_0}{T_I} \sum_{i=1}^{k} e(i) = u_I(k-1) + K_P \frac{T_0}{T_I} e(k) \tag{11}$$

$$u_D(k) = K_P \frac{T_0}{T_I} [e(k) - e(k-1)]$$

PID controllers can be applied to most existing industrial processes, they are designed to simplify the work of operators and exercise better control over operations. Some of the most common applications are:

- Temperature Loops (Air Conditioning, Heaters, Coolers, etc.)
- Level loops (Level in tanks for liquids such as water, dairy, blends, crude oil, etc.)
- Pressure Loops (to maintain a predetermined pressure in tanks, pipes, containers, etc.)
- Flow Loops (maintain the amount of flow within a line or tube)
- Speed loops (conveyor belts, rotation speed in motors).

3. AUTO-TUNING

The identification system plays a key role in the automatic tuning of the PID controller. Based on the information obtained, the identification methods can be classified into frequency domain and time domain [6], [7].

The tuning rules of the controllers can be divided as follows [8]:

- Tuning rules based on one-step response measurement
- Tuning rules based on the minimization of an optimization criterion
- Tuning rules that deliver a specific closed-loop response Such rules group closed-loop pole designs and phase margin and gain margin designs.
- Robust tuning rules, offering solid stability with performance criteria built into the process
- Tuning rules based on recording the appropriate parameters at a maximum frequency (also known as end-cycle methods).
- Other tuning rules, such as tuning rules that rely on a proportional gain to achieve a decade-by-decade attenuation ratio or to achieve a particular magnitude and frequency in a particular phase.

Several tuning rules can belong to more than one subdivision, so these divisions are not mutually exclusive. In the time domain, responses are generated from step or pulse tests. The characteristics of the plant response are used to recalculate the process model parameters. The step tests can be performed in an open circuit (manual mode) or closed-loop (while the controller is working). However, it is vulnerable to load disturbances, especially for systems with large time constants.

Another category is the experimental design developed by Ziegler-Nichols. Probably the most successful part of the Ziegler-Nichols methods is not the tuning rule itself. Rather, it is the identification procedure: a way to find the important plant information where K_u and ω_u are defined. A typical approach can be summarized as follows:

- Set the proportional gain of the controller to a small value, it can be 0.2
- Set the controller to automatic mode
- Make a small change in the reference signal and observe the response.
- Increase the proportional gain by a factor of two and change the reference signal again.
- Repeat the previous step until the plant starts to oscillate and a continuous cycle is observed.

The gain for which the plant oscillates is K_u and the period of oscillation P_u. This is a simple and reliable method of obtaining K_u and ω_u. The disadvantage is also obvious: it requires a lot of time. The current version is the

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relay test, proposed by Åström and Hägglund [9]. First, a continuous cycle of the controlled variable is generated from the relay feedback and the important information, Ku and ωu, can be extracted directly from the experiment. The information obtained from the relay feedback is the same as that of the conventional continuous cycle method.

In the industry, poor controller performance can have several reasons. For plant identification, it must be recognized that the controllers are working with imperfect valves, noisy sensors and frequent load disturbances. These factors must be taken into account when designing the experiment to find the controller parameters [10], [11]. To perform the auto-tuning process there are several algorithms among which we can mention:

- Dahlin PID controller
- Bányász and Keviczky PID controller
- Pole assignment methods for digital PID controllers
- PID controllers based on Ziegler-Nichols criteria

4. DESIGN OF CONTROLLER

4.1 General Features

The PID controller was designed to integrate four unique PID controllers into a single device to save space, components and money. The controller makes use of an existing digital PID algorithm with some modifications or additions to fit the designed hardware.

The operator menu allows a simple and intuitive way to navigate through the controller options, giving you the ability to make hot or cold configurations without affecting the operation of the unmodified loops. It also allows configuring the variables of each PID loop separately, this option is available both in operation and in standby, each PID loop is activated or deactivated by operator decision.

The use of the controller is recommended for plants that have a setup time of no less than 100ms. Additionally, the controller can perform auto-tuning to each separate loop and set the constants to suit the plant. It can be applied in plants that do not take more than 20 minutes to reach their operating point otherwise the calculated values may not be adequate and result in a loss of efficiency and even possible instability of the plant.

On the controller screen, the user can observe the controller variables in real-time. In addition to the menu options, the controller has three LEDs per loop that allow the operator to view active PID loops, saturated loops, and loops with a current greater than 500 mA. Each PID loop operates in the range 0 - 10 V for inputs and outputs. The controller physically has four inputs/outputs, a power supply connection and a USB port for connection to a PC.

The technical specifications of the controller are summarized in Table-1.

Table-1. Technical specifications of the controller.

CONTROLLER FEATURES	
Maximum supply voltage	26 VDC
Minimal power supply voltage	20 VDC
Auto-tuning	YES
Manual tuning	YES
Number of control loops	3
Inputs available	3
Available Outputs	3
LCD screen	Alphanumeric 16x2 characters
Keyboard	Matrix 4x4
Power switch	YES
Input signal	0-10 v
Output signal	0-10 v
Minimum Kp	1E-3, includes zero value
Maximum Kp	999E+3
Ti minimum	1E-3 sec
Ti maximum	999E+3 sec
Minimum Td	1E-3 sec, includes zero value
Maximum Td	999E+3 sec
Set point range	(0 - 99.9) %
USB port	YES
Parameter setting via LCD and keyboard	YES
Loop saturated indicator light	YES
Configuration of parameters via PC	YES
Loop in operation indicator light	YES
Maximum output current per loop	500 mA
Independent ground for each loop	NOT
Mode P	NOT
PI mode	NOT
PD mode	NOT
PID mode	YES
PID SISO	YES
PID MIMO	NOT

4.2 Controller Scheme

Taking into account the design conditions of the controller device indicated above, a general scheme is proposed with the electronic elements that will integrate the multiloop controller device. Figure-1 shows a general

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design scheme with the main elements that make up the controller device.

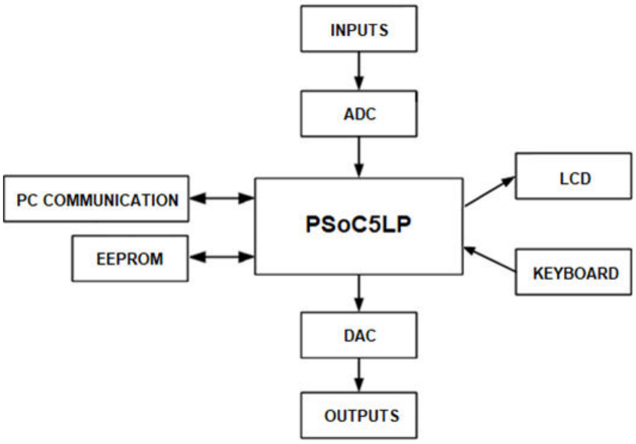

Figure-1. General diagram of the controller.

Each of the elements proposed in Figure-1 has a series of characteristics, requirements and qualities described below:

INPUTS:
- Operating range 0 - 10 V.
- Protection against voltage levels below zero.
- Protection against voltage levels higher than 10 V.
- Conditioning of the input signal to be converted to a digital signal.
- Passive low-pass input filter.
- Light indicator proportional to the input voltage level.

ANALOG-TO-DIGITAL CONVERTER
- Converter integrated into the PSoC5LP.
- 12 bits converter.
- 4 input channels

MAIN PROCESSOR
- PSoC5LP Cortex-M3 32-bit
- Processes all 4 operating loops simultaneously.
- It delivers the processed data to the digital-analogical converter.
- Control of the user interface.
- Storage of parameters and data.
- External communication control.

DIGITAL-ANALOG CONVERTER
- Converter integrated into the PSoC5LP.
- 12 bits converter.
- 4 converters with independent outputs.

OUTPUTS
- Conditioning of the signal delivered by the digital-analog converter.
- Operating range 0 - 10 V.
- Elimination of voltage levels below zero.
- Protection against short circuits at the output.
- 500mA power output per loop.
- Light indicator proportional to the output voltage level.

USER'S INTERFACE
- LCD
- Matrix interaction keyboard.
- Light indicators for active, saturated or short loops.
- Light indicator for device energized.

POWER SUPPLY SYSTEM
- 5 VDC main power supply.
- Other devices powered by 24 VDC.

MECHANICAL CONSTRUCTION
- Connection to the outside utilizing screw terminals.
- Grounded metal housing.

4.3 Implemented Hardware

4.3.1 0-10v inputs

The inputs of the controller device by design must receive signals between 0 and 10 V, however, the PSoC5LP´s analog to digital converter can only receive signals between 0 and 5V. This is why a signal attenuator is used which performs the voltage conversion by delivering a maximum of 2V, equivalent to the 10V that entered the device initially.

The conversion ratio is equal to that shown in (11).

$$v_0 = Gv_i \qquad G = \frac{v_0}{v_i} = \frac{2}{10} = 0.2 \tag{11}$$

Therefore, the resistance ratio for a resistive divider is given by (12).

$$G = \frac{v_0}{v_i} = \frac{R_2}{R_1+R_2} R_1 = 40k\Omega R_2 = 10k\Omega \tag{12}$$

If the input signal is connected directly to the resistive splitter, depending on the impedance coupling, the signal may be altered and the loop would work with wrong information, which is why a resistive splitter is placed after an operational amplifier. Also, taking into account that the working environment of the controller device is of industrial-type and that it can come into contact with signals that exceed 10 V, as well as with signals that are below 0V, a protection system is included in the design of the inputs as shown in Figure-2. To attenuate the noise coming from the working environment and not to affect the signals being worked with, the filter is designed for a cut-off frequency of 1kHz.

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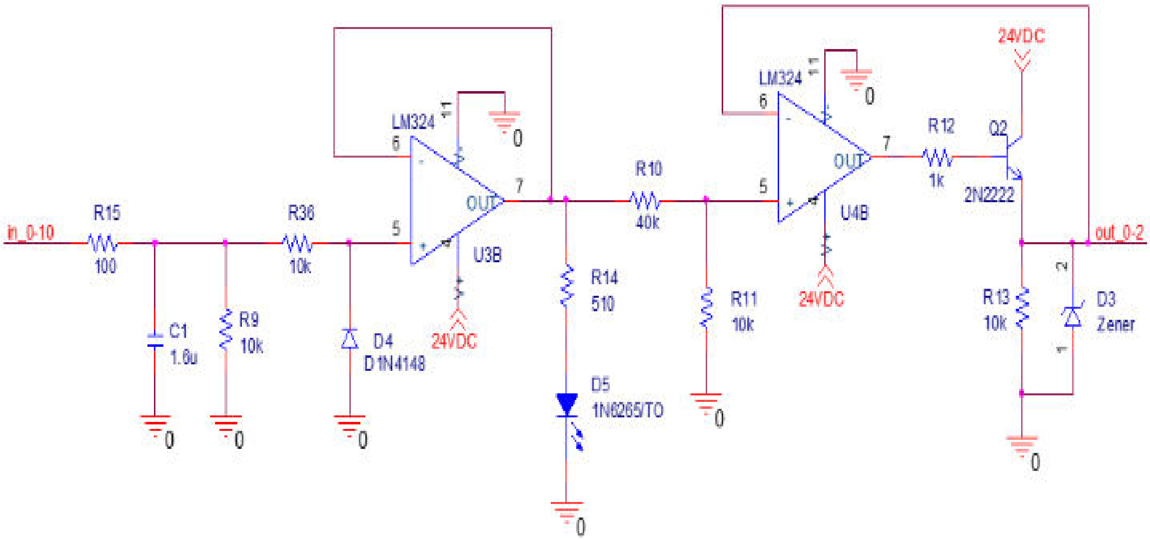

Figure-2. Input signal conditioner.

4.3.2 0-10v outputs

The PSoC5LP has four internal Digital to Analog converters (DAC) that limit its voltage output to 1024 V or 4096 V [12], [13], this is why it was standardized that both the signals entering the PSoC and those leaving it are in the range 0 - 2V, additionally, this contributes to make the system independent of the exact power supply value.

To obtain the desired output in the range of 0 to 10v requires an external operational amplifier in non-inverting configuration, also requires that the output can provide a current level of up to 500mA, so it is required to add a current driver to support such a load. The current will be supplied by a transistor array in a Darlington pair configuration and an operational amplifier that regulates the level of voltage supplied, which also includes a short circuit or over current output protection system. Figure-3.

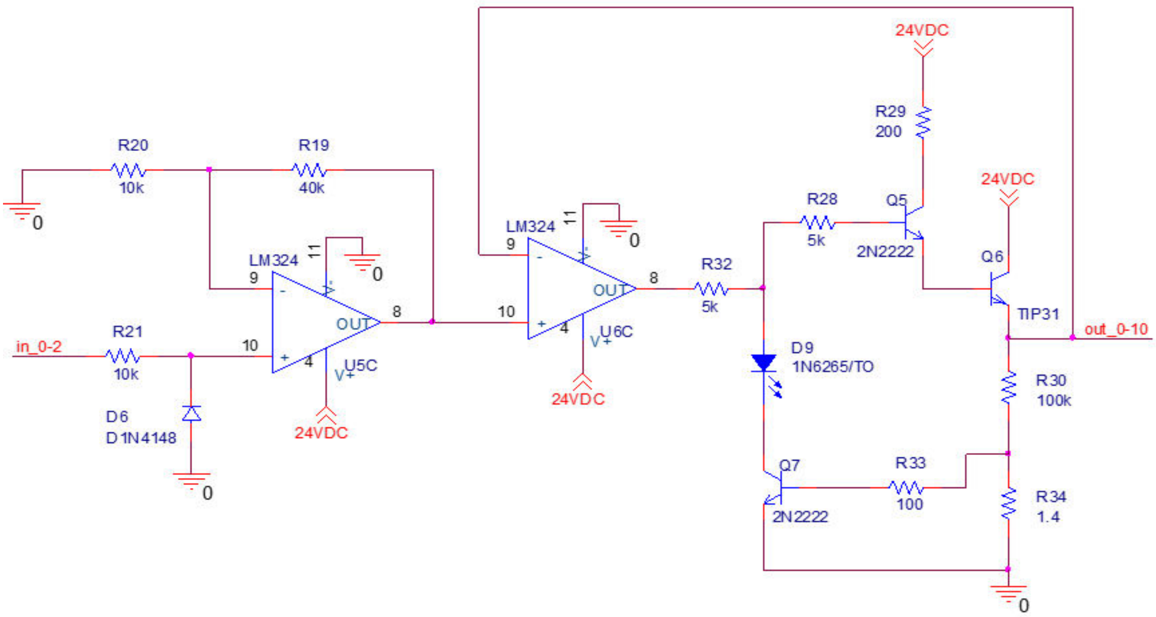

Figure-3. Output signal conditioner.

To verify the operation of the design, a simulation was carried out, in which a load of 0.5 Ohms is connected to the output, a value with which at 10 V a 2A supply of direct current would be required, verifying that the current limiter enters into operation limiting the current to 500mA, with which the output voltage level only reaches 0.25V, complying with the protection of the device (Figure-4).

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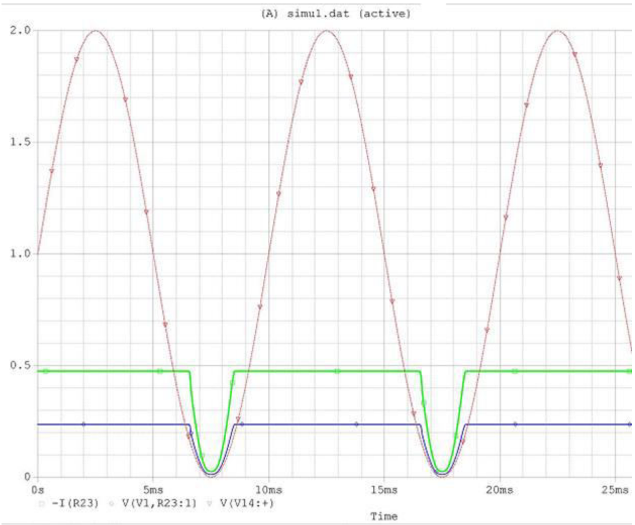

Figure-4. Over-current output protector simulation test.

4.3.3 Indicators and warnings

The controller has a series of indicators that allow the user to check the status of each control loop and its correct operation at any time without having to access the main menu.

The list of indicators available to the device is listed below:

- An LED indicates when the controller has been energized. In standby status, the LED indicates whether the device is powered with 24VDC or if there is no power to the device.
- Four separate LEDs indicate whether the control loop has been activated or whether it is off.
- Group of four LEDs that are activated separately in case the controller output has reached its upper limit and is saturated.
- Four LEDs that indicate when the output of a control loop has reached its maximum current delivery level set at 500mA per loop. Their main function is to detect the presence of a short circuit at the controller output.
- Group of four LEDs that indicate to the user through their brightness the level of voltage proportional to the controller input. The minimum level is 0 V for the off LED and the maximum level is 10 V, where the LED will have its maximum brightness.
- Four LEDs that indicate to the user by their brightness the level of voltage proportional to the output of the controller. The minimum level is 0 V for the off LED and the maximum level is 10 V, where the LED will have its maximum brightness.

Accordingly, the user can establish the presence of faults that may affect the proper functioning of the system by simply checking the status of each of the above-mentioned LEDs.

Additionally, if the user wishes to verify the internal parameters and variables of a control loop, he can access this data through the user menu. The LCD will allow the user through simple and intuitive navigation to access the data at the time required. The menu also allows you to perform control tasks, configure parameters and display other variables.

The interaction with the user menu is done by manipulating a 4x4 matrix keyboard and the display is presented on a 16 character, two-line LCD. With the elements mentioned throughout this section, the user would be able to manipulate the configuration and make use of the controller designed here.

4.3.4 Data storage

The internal EEPROM memory of the PSoC5LP, which has a capacity of 2KB and allows it to be written and read at any time without any restriction, is used to store the configuration and operating parameters of the controller.

The EEPROM component provides a set of APIs to delete and write data to the EEPROM memory included internally in the PSoC5LP The term writing implies that the will delete and then program the memory in a single operation. The EEPROM memory in PSoC devices are organized in arrays, the PSoC3 and PSoC5LP devices offer a memory size 512 bytes, 1KB or 2KB, depending on the device reference to be used. The EEPROM matrix can be divided into sectors having up to 64 rows with a size of 16 bytes.

The application programming interface (API) routines allow you to modify a complete EEPROM row, individual EEPROM bytes or delete an entire EEPROM sector in a single operation [13].

4.3.5 Final design

For the implementation of the prototype, the design of the printed circuit board is divided into three sections to facilitate implementation and to reduce the size of the controller.

The first is the card dedicated only to coupling the plant inputs (loop feedback), so that it can transfer the signals to the PSoC5LP under the conditions specified for the ADC (Figure-5). This card counts the terminals dedicated to the connection of the inputs of each loop and transfers their signals through a bus. LEDs proportional to the incoming voltage level on the board are located near their respective terminal block as a verification tool for the user in case of faults in the loop.

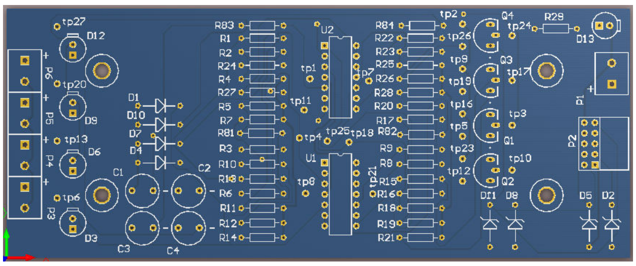

Figure-5. Card for handling the controller inputs.

The second card contains the signal and current drivers to be delivered as a control signal to the plant in

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each loop. This card uses the highest current levels of the whole device, for this reason, it has wider paths in the PCB and integrates the power supply terminal block, to make the lowest high current path through the whole controller.

This card, besides receiving the control signals from the processor through a communication bus, must transfer and close the circuit of the LEDs that indicate a short circuit on the front of the controller (Figure-6). A special arrangement is designed for these LEDs to transfer this signal to the panel and to easily perform internal tests of the protection circuit.

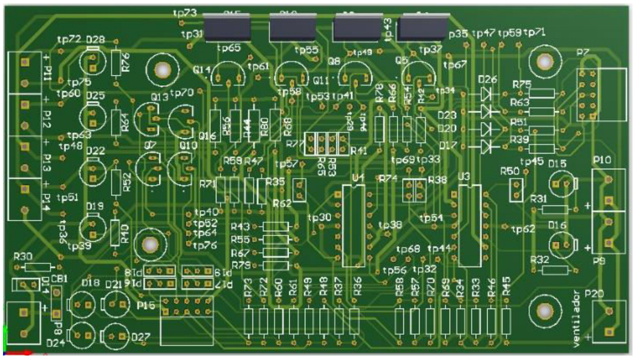

Figure-6. Card for handling the controller outputs.

As the controller output board has the external power supply terminal block, power is supplied to the other boards through the additional terminal blocks placed internally to supply the input board, control board and finally a fan to dissipate heat.

The third card contains the PSoC5LP, connection to the LDC and the keyboard and all the visual elements used to display controller states, the card is located on the front panel of the controller.

4.4 Software Design

The entire set of instructions that are interrelated to perform the processes defined for the device is called the device software. The software is embodied in the programs designed and implemented for the PSoC5LP and in the program executed from the computer to interact with the device.

The main purpose of the PSoC5LP is to process and calculate the variables related to each of the control loops from the pre-established control parameters. From the above, it can be concluded that the device needs to configure the parameters of the control loops and then store them before starting operation (Figure-7).

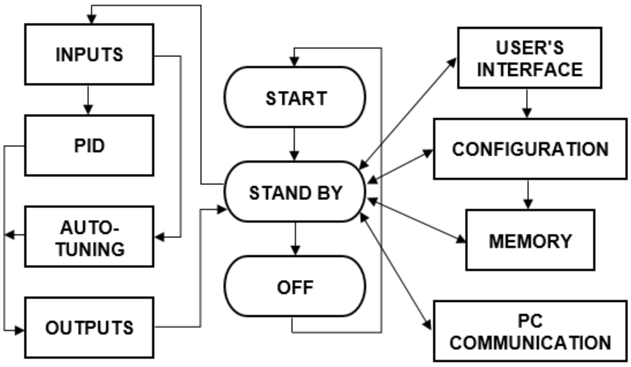

Figure-7. Controller task diagram.

The software executed in the PC can configure the device and present data of interest to the user, in Figure-8 you can see the logic used to generate this process.

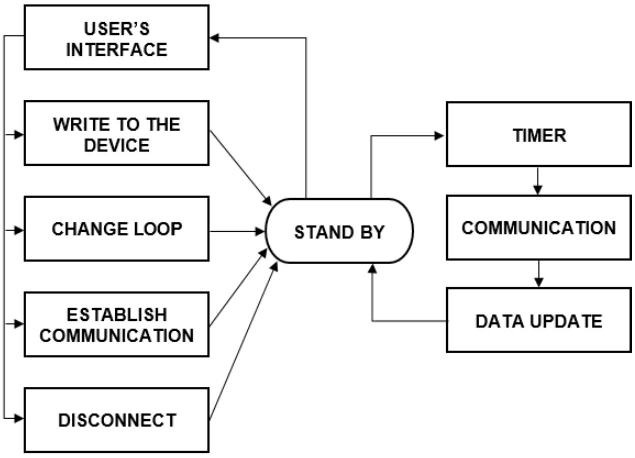

Figure-8. PC task diagram.

4.4.1 PID control algorithm

The selected PID control algorithm corresponds to the parallel recurrent algorithm shown in (10), which facilitates its implementation using only three variable storage records and independent calculation of each controller component.

To this algorithm a filter is added for the derivative component as shown in (13), a limit for the maximum value of the output to avoid accumulation in the integral component when the controller has been saturated and finally a lower limit equal to zero to avoid the decrease of the integral component when the output value has reached the minimum.

$$d(k) = \frac{(2T_D - \alpha T_0)d(k-1) + 2K_P T_D \alpha[e(k) - e(k-1)]}{2T_D + \alpha T_0} \qquad (13)$$

The controller's output value calculation algorithm consists of 4 different parts in: data acquisition, output calculation, output correction and output update.

- Data acquisition consists of acquiring the data from the PSoC5LP's ADC module and scaling it to use it

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internally as a floating-point value between 0 and 65535 equivalents to the 0 to 10 V of the device's electrical input.

- To calculate the controller output, first, the error value for that cycle is obtained, then the Proportional, Integral and Derivative contributions are calculated and finally, they are added to obtain the full value of the PID controller output. Within the calculation of the derivative contribution, the filter shown in (14) is included, with an experimental value determined for α=10.

$$u_D(k) = K_P \frac{T_D\alpha}{T_D+\alpha T_0}[y(k-1)-y(k)] + \frac{T_D}{T_D+\alpha T_0}u_D(k-1) \quad (14)$$

- Output correction is given when the calculated value for the output exceeds the value of 65535 or is less than zero. For the maximum output value, the controller maintains the same previous value of the output preventing the integral component from increasing further. For the opposite case, all the components are equal to zero so that the device delivers the minimum as a response to the control being exercised on a plant that exceeds the set point and does not go down further by external agents.
- To finish the algorithm, the data of the calculated components are saved in a register and the output of the controller is updated in the DAC converting the data into electrical signals between 0 and 10 V.

The algorithm can be extended to several loops if at the beginning all the inputs of the ADC module are read and their equivalents are temporarily stored (Figure-9). It is then determined whether the loop should run the calculation for that instant of time depending on the sampling time.

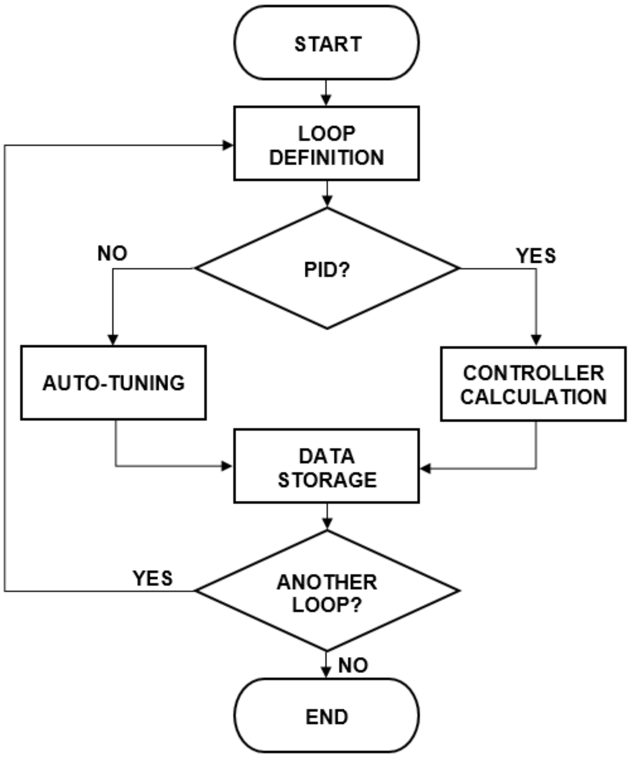

Figure-9. Control algorithm.

Once you have determined the loops to be executed for a new control calculation, the specific loop data is loaded, calculated component by component, and stored in the record defined for the running loop. When all the loops have been processed, they are updated simultaneously on the controller outputs and the cycle is terminated.

4.4.2 Auto-tuning algorithm

The auto-tuning system used is based on the Ziegler-Nichols experimental method; however, it does not follow it to the letter as this only works for some types of plants. Therefore, additional calculations are used to induce an oscillation in the plants to be controlled.

Using the free oscillation of the plant the value of the parameters necessary to determine the constants of the PID controller is obtained. As the purpose of the method is to find the ultimate proportional gain and the ultimate time of oscillation of the plant, the process starts with the characterization in time and gain of the plant in an open loop.

To carry out this process, a step is given as a plant excitation signal at 30% of the total working range of the plant. The plant will increase its signal level to a specific point where it will stabilize after a time determined by the nature of each controlled plant.

Once the plant is stabilized, the first step for the auto-tuning is completed. From here we obtain the output of the plant Y_1 and the stabilization time of the same t_{est}. Through the output of the plant and the setpoint sp, the gain k_1 is calculated. The twentieth part of the stabilization time is used as sampling time, if this is less than 10ms; it is left at 10ms as sampling time (15).

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$$k_1 = \frac{Y_1}{sp} t_0 = \frac{t_{est}}{20} \tag{15}$$

To obtain the oscillations, a step height value h is determined by which the plant is switched and thus constantly oscillates. To this end, the value of h is modified using the gain k_I and given a little more gain to obtain the oscillations in a forced way, as shown below. The switching points are:

$$Y = Y_1 \pm h \tag{16}$$

For this the output signal varies between:

$$U = sp \pm \frac{1.2h}{k_1} \tag{16}$$

The second part of the auto-tuning consists of starting the oscillation of the plant until 30 rising edges are completed, in this way a constant oscillation can be obtained and the 20 samples necessary to calculate the values of the last gain and the last period of oscillation can be taken.

Once the 20 samples have been taken, the controller output is taken to zero by turning off the plant and the calculation of the last gain and last oscillation period begins. For this purpose, the time between two peaks or two valleys and the amplitude of oscillation is measured.

$$k_{cu} = \frac{4h}{\pi A} \tag{17}$$

Having determined the ultimate gain K_cu and the period of oscillation P_u, the parameter tuning of the PID controller can be obtained according to (18).

$$K_p = 0.6K_{cu} T_I = 0.5T_u T_D = 0.125T_u \tag{18}$$

According to the above, the system would calculate the parameters of the PID controller and before being put into operation it asks the user if he wants to keep those parameters, if he wants to calculate them again or if he prefers to enter them manually.

4.4.3 Inputs, outputs, LCD and keyboard

The inputs and outputs interact with the conditioning circuits with voltage levels between 0V and 2V. The inputs are obtained through the ADC module integrated into the PSoC5LP, which operates with a 12-bit resolution. The result of the conversion is stored in a 16-bit register, so an adjustment is made so that the maximum and minimum input values correspond to the 65535 and zero limits.

Every 10ms the PSoC measures the input of the 4 control loops, however, only if the loop sampling time corresponds to the sample taken, the control calculation is made. The output is only updated each time the control calculates a new value for a certain loop. In Figure-10 you can see the PSoC5LP resources used for the controller implementation.

The inputs Vin_CH1 to Vin_CH4 are connected to each of the conditioning circuits shown above in Figure-2. Similarly, the outputs Vout_CH1 to Vout_CH4 are connected to the circuits that set the output to the 0-10v range shown in Figure-3.

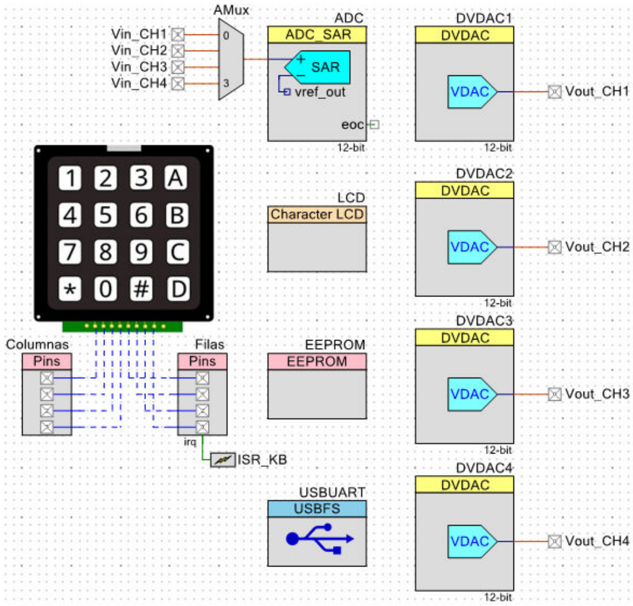

Figure-10. Implementation used in the PSoC5LP.

The user interface consists of a matrix keyboard and a two-row x 16-column LCD, sufficient to interact with the controller. The keyboard is controlled by an interruption of the PSoC5LP (ISR_KB), with which the key pressed by the user is recognized and its function is determined according to the segment in which it is in the user menu.

The LCDs different information for each user menu segment, allowing the user to navigate through the controller options identifying where they are. The entire interface is dependent on a user menu designed for easy access and scrolling through the various options.

The menu is divided into two main processes, the first allows the user to interact with the controller options before starting operation and the second complements the operation by giving the user additional options when the controller is already operational.

5. TESTS AND RESULTS

The device test scheme is divided into three parts, with which the operation and capabilities of the device are verified. The device has two main operating characteristics contemplated in the operation which are PID control and self-tuning of the device. The first two tests are focused on this point to verify the reliability of the device. Thirdly, the electronic protections that were used in the device are tested to avoid severe problems on the electronics due to common manipulation errors.

Initially, the execution of the control algorithm will be tested using a manual tuning that will be compared with the simulated response using a mathematical analysis

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program. To obtain the values, the Integral of Time multiply by Absolute Error (ITAE) optimization method is used, with which the most suitable parameters for the tuning of the plant are determined.

In principle, the response of the plant in an open-loop is checked with a pass signal against the response in plant simulation. Then the controller is tuned and compared to the response obtained in the simulation.

The same is done for four process plants with different time constants and both over- and under-damped step responses.

The second test corresponds to the auto-tuning algorithm implemented in the device. Two main elements of this algorithm are checked. First, it is verified that the parameters calculated for the same plant are always similar since the tuning process is the same. Secondly, a comparison is made against the manual tuning performed in the first part of the tests and the response obtained from the plants. Since the point of comparison is an optimized response, the algorithm must comply with performing control of the plant, but not equal the level of manual tuning.

The Figure-11 shows the response of two floors to which the auto-tuning process is performed simultaneously.

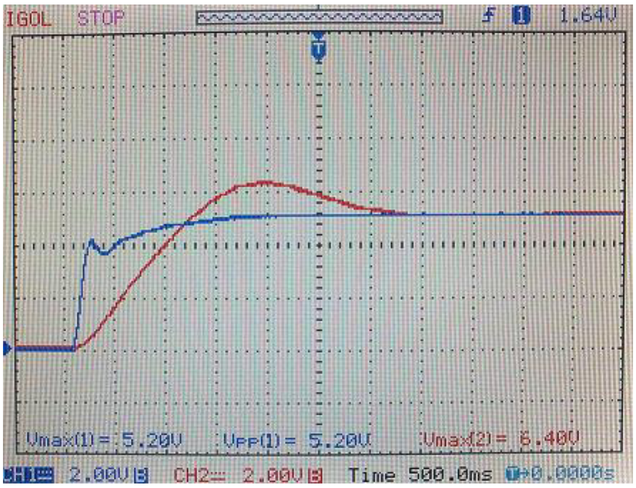

Figure-11. Two plants controlled by an auto-tuned PID.

The last part of the tests is directed to the reliability of the device against bad manipulation and resistance to working conditions out of the specified ones but that can be presented in a normal working environment. The first test confirms the device's ability to withstand short connections, always delivering the 500 mA specified for the prototype. A second point, the resistance of the circuit to inputs higher than 10V, the limit of the input range, is checked.

The control algorithm performed well when used in fast-moving plants. The three members of the PID controller were tested and obtained the expected results. The operation of the proportional and integral controllers was correct and the plants tested showed a response very similar to the data obtained in simulation.

The sampling time is a factor that determines much of the stability and good execution of the processes. According to the theory, the sampling time should be proportional to the response time of the plant being controlled; however, the sampling time has a relevant role in the execution of the control algorithm. Due to this reason, different experiments were carried out to determine the sampling time according to each control plant. However, it was not possible to obtain a clear criterion and if enough limitations were found in the increase of the sampling time, even if the plant dynamics were slow.

The auto-tuning algorithm used is based on Ziegler and Nichols' idea of auto-tuning a plant according to its natural frequency of oscillation and the amplitude of that oscillation. However, this system does not work properly in overdamped plants, so it was necessary to include a series of instructions to force the oscillation of this type of plant. Once the control parameters were obtained, it was observed that the response of the plants was excessively slow, so another set of instructions is added to improve this aspect in the auto-tuning of each plant.

6. CONCLUSIONS

The tests revealed a good behavior of the control algorithm, while the auto-tuning algorithm should be re-evaluated since it presents a simple way to reach some parameters for the PID controller, this is not effective in the response times of the plant, which is why it should include more auto-tuning options for the different cases of plants it can control. The interface of the controller has to be rethought if you want to make the device modular or if you want to maintain the whole, there is currently a wide range of Tablets and similar that can be adapted to the application.

The auto-tuning algorithm generates controllers with slow dynamics concerning the dynamics of the plant, which is why its stability is guaranteed for a wide variety of processes. These slow dynamics favor the rejection of disturbances in the control signals and improves their response to noise. However, not all applications require a controller of this type, so the device must include a greater variety of auto-tuning options so that the user can select the one that best suits his application.

When the driver is in its control state it is protected to withstand unstable behavior, however, it is the responsibility of the user to monitor the behavior of the process to take safety actions if the situation warrants. When the controller performs the auto-tuning process, the nature of the plant can reach unstable behaviors, so it must be taken into account for future developments, the actions to be taken to perform safe auto-tuning, both from the equipment, as well as the user.

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