Design of an embedded PID controller applied to blood pressure control

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***Abstract*— Some diseases, such as hypertension, require a close control of the patient's blood pressure. This is even more critical when that patient is going through – or has just underwent – a surgical procedure In such situations, reducing blood pressure to normal levels is of paramount importance. Usually, this demanding and time consuming monitoring is done manually by clinical personnel and are subject to mistakes and inconsistent practices. In this paper, we propose a solution to the manual monitoring through the design and implementation of an embedded PID controller to handle blood pressure, integrated to an automated monitoring system to assist in detecting anomalies and to optimize the process of patient care.**

I. INTRODUCTION

ONE issue experienced by doctors and health professionals is to monitor the patient's vital signals in real time and to control the drug injection if it is necessary. Some anomalies such as high blood pressure (hypertension) need to be controlled as soon as possible in order to prevent further damages, especially during surgery and post-surgical cases.

Arterial hypertension is an important risk factor responsible to cause cardiovascular diseases, being responsible for 40% of the deaths caused by coronary arterial disease. Twenty-nine percent (29%) of the world population has arterial hypertension and in Brazil the number goes from 22% to 44% depending on the region [9]. These numbers become extremely important as high blood pressure is directly related to cerebrovascular events, coronary arterial disease and mortality [5].

In order to reduce the risk of postoperative complications, the blood pressure needs to be controlled in a quick and effective way. One way to achieve this is to apply the infusion of vasodilators drugs such as Sodium NitroPrusside (SNP). However, an overdose of the drug can cause serious and undesirable side effects.

Each patient has, usually, a different sensibility to the drug and this, in general, varies with time. Thus, there must be a continuous blood pressure monitoring and frequent adjustment of the drug infusion rate in order to maintain blood pressure at an appropriate value [14]. The manual control is very laborious because it requires continuous monitoring. Peculiarities such as delays in the response of the circulatory system, the wide range of the patients' sensitivity to the drug and the continuous changing on the patients characteristics over time, make this work a tracking and difficult task that requires extra attention and responsibility.

Given the problem presented, we have proposed a two part project: (i) the implementation of an embedded PID controller with identification , tuning and adaptive techniques in order to control the patient's blood pressure by SNP infusion, until the patient receives appropriate medical care; and (ii) the development of an remote monitoring system to send alerts to doctors and family[12]. This paper presents the development of the first part (control part) of this project.

Due to the importance of the problem reported here, the literature provides numerous studies with techniques and control algorithms applied to blood pressure control, such as: (i) Reference model adaptive controller, used by Pajunen et al [10], (ii) Predictive adaptive control written by Maitelli & Yoneyama [7], (iii) Intelligent control (fuzzy and neural network systems) founded in Polycarpou & Conway [11].

However, the biggest challenge of the present work is to embed these techniques considering that the hardware used to embed it does not provide high performance and large memory space. As references of embedded control applied to blood pressure were not found in the literature, it is necessary to start with a simple PID control without adaptive techniques, and then in the future to improve the algorithms to be embedded. However, this controller has to be efficient enough and must have adaptive characteristics. Then, the proposed solution is to split the control in two parts: embedded and non-embedded. Where more advanced algorithms will be used, in a powerful non-embedded computer, to select the best controller for the chosen patient and then, the embedded system is going to be configured with those founded controller parameters.

II. MATHEMATICAL MODELING

The model of Mean Arterial Pressure (MAP) from a patient under the influence of sodium nitroprusside (SNP) developed by [13] is given by:

$$\boldsymbol{MAP(k) = y(k) = P_0 - \Delta y(k) + v(k)} \qquad (1.1)$$

where MAP is mean arterial pressure, P_0 is the initial blood pressure, Δy Y is the change in pressure caused by the SNP infusion and $v(k)$ is a stochastic noise.

A continuous model describing the relation between pressure variation $\Delta Y(s)$ and the drug infusion rate $I(s)$ is given as follows [10]:

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$$\Delta Y(s) = \frac{K_s e^{-T_i s}(1+\alpha e^{-T_c s})}{1+\tau s} I(s) \qquad (1.2)$$

where ΔY is the arterial blood pressure variation, I is the infusion rate, K_s is the sensibility to the drug, α is the recirculation constant, T_i is the initial transport delay, T_c is the recirculation delay and τ is the time constant.

According to Slate [19] and Kaufman [4], P_0 is usually between 115-140mmHg and $v(k)$ 2-5mmHg (for low noise level) and 15-25mmHg (for high noise level). The others parameters vary according to [10].

The corresponding discrete model for this process can be given by the following equation [15]:

$$\Delta y(k) = \frac{q^{-d}(b_0 + b_m q^{-m})}{1-a_1 q^{-1}} I(k);\ b_0 \geq 0 \qquad (1.3)$$

where q^{-1} represents the delay operator. The parameters b_0, b_m, a_1, d, and m are obtained from the discretization of the continuous model equation (1.2) using a zero-order hold.

III. SYSTEM DESIGN

As it was mentioned before, the whole project is divided in two parts (Figure 1): The control part, named ControlCare (CC) and the monitoring part, named AngelCare (AG) [12]. This paper is focused only in the ControlCare development.

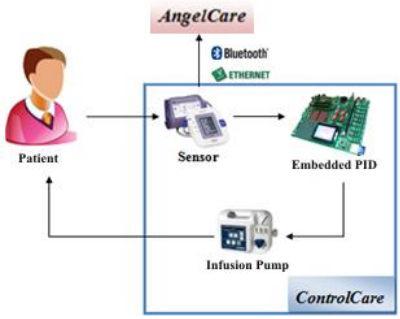

Figure 1-Proposed system diagram.

The ControlCare design is also divided in two parts: embedded and non-embedded as the Figure 2 shows.

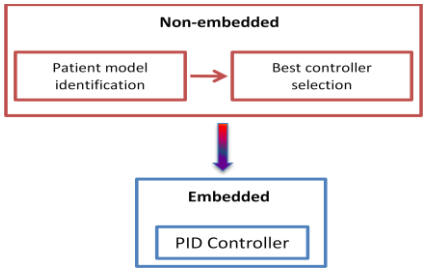

Figure 2- ControlCare schema.

Adaptive and more elaborate algorithms will be implemented in the non-embedded system which has 4 steps: identification, bank of controllers, controller selection and optimization selection, as it can be observed in the Figure 3.

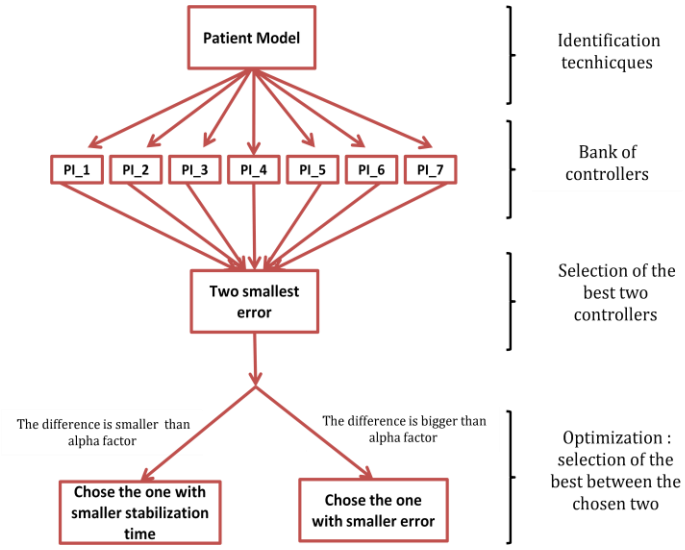

Figure 3. Block diagram for the best controller selection

A. *Identification techniques*

The first step is to obtain a valid patient model and to succeed it is necessary to use systems identification methods. The Figure 4 shows the process used to obtain a valid mathematical model. The techniques used to adjust the parameters are yet to be tested but it will be used an identifier that consists basically of the least square parameters estimator with a forgetting factor algorithm.

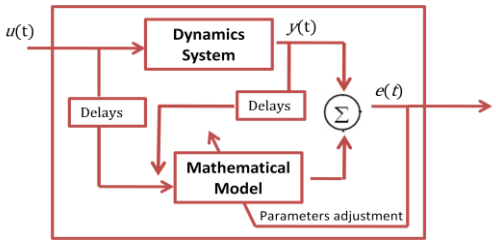

Figure 4. Patient model generator.

B. *Bank of controllers*

For a consistent project design some input and output restrictions (R1, R2 and R3) have to be considered [13]:

- Input: the eligible SPN infusion rate I(t) range is:

$$0 \leq I(t) \leq 180\ ml/h \qquad (R1)$$

- Output: the maximal variation rate of the patient MAP in a 15s sample interval is:

$$|\Delta MAP(t)| = |PAM(t-1) - PAM(t)| \leq 15\ mmHg \qquad (R2)$$

- Output: the pressure must not drop more than 20mmHg under the setpoint. In this project the setpoint used is 100mmHg, then the minimum acceptable value for the pressure is:

$$MAP(t) \geq 80\ mmHg \qquad (R3)$$

The project was based in the equation 1.2 used to represent the patient behavior and the equation 1.1 which adds a noise

and the initial blood pressure in order to obtain the MAP.

To design the bank of controllers, seven controllers were tuned according to each patient represented in table I. In the tuning process (Figure 5), all the restrictions mentioned above were satisfied.

TABLE I.
Patient-Models Parameters.

Patient	Gain K_s	Time t	Delay T_i	Delay T_c	Gain α
1	0,25	30	20	30	0
2	0,25	60	60	75	0,4
3	0,625	35	30	37,5	0,1
4	1	40	40	45	0,2
5	5	50	50	60	0,3
6	9	60	60	75	0,4
7	9	30	20	30	0

The parameters chosen to represent the patients-model in Table II were generated by a combination of the related variables values on [10], for example: patients with high sensibility and high delays, high sensibility and low delays, low sensibility and low delays, as well as its nominal and mean values resulting, then, in seven different patients covering a wide range

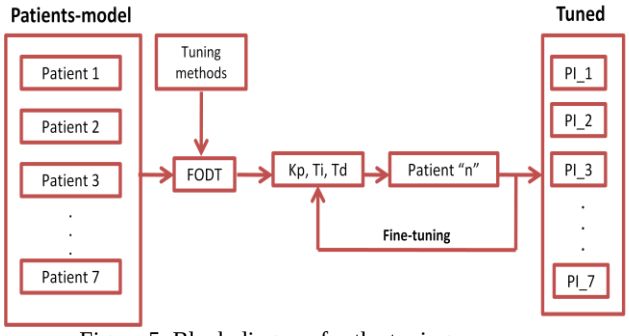

Figure 5. Block diagram for the tuning process.

In the tuning process shown in Figure 5, the FODT (first order plus delay time) function was founded for each patient and then the tuning methods, Ziegler e Nichols(ZN) [16], Chien, Hrones e Reswick(CHR) [1], Cohen e Coon (CC) [2] , error integral [6]and fine-tuning ,were applied in order to find controllers that would satisfy all the conditions R1,R2 and R3 and show a good performance.

The controllers and methods that showed best results were PI controllers with error integral methods. That's why the figures are showing PI controllers instead of PID, but the implementation is the same differing only because in the PI controller the derivative factor is zero.

C. Selection and optimization

After the tuning process, the bank of controllers is complete and it will be used to select the best controller to the generated patient. The selection works comparing the errors generate by each controller and choosing the two with the smallest errors. After, there is an optimization that will choose between the bests two. This process uses an alpha factor (usually close to one (1)) that demonstrates how close the two errors are. If the two errors are not close (|error1-error2|>alpha), the controller that shows the smallest error is chosen, else (|error1-error2|≤ alpha) the controller that shows the smallest stabilization time is the chosen one.

D. Tests and Results

Several tests were performed with various models of patients and Figure 6 shows the result of a simulation, in which the patient's parameters were:

K_s= 0.9137; t = 31.6185; T_i=41.2319; T_c=65.0625 and α=0.3736.

The parameters of PI controllers selected by the bank of controllers were: K_p=0.7500 and K_i=0.0140.

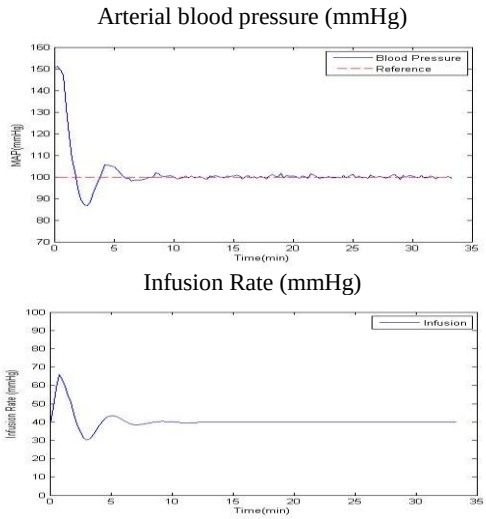

Figure 6. Patient's MAP and infusion rate.

Some values used were: an initial blood pressure P_0 of 150mmHg (representing a hypertension case), a setpoint of 100mmHg, a maximum saturation of 180 ml/h (R1) and an white noise of 4 mmHg (low level) [4][13].

IV. EMBEDDED SYSTEM DESIGN

For the design of the embedded PID, the simulation environment Proteus [3], which allows the simulation of analog and digital electronic circuits simultaneously, was used. Therefore, it is possible to evaluate, for example, if the designed PID controller works properly. It was used a PIC18F4520 (Figure 8) microcontroller and features providing an automatic configuration of the controller via a virtual terminal that simulates communication with a computer via serial port RS-232, thus the programmer does not have to change the code to change the parameters. The user can either configure the PID, by typing "C", (Figure 7) or can read the data from the EEPROM, by typing any other letter. For the simulation we used a first order plant with delay. The compiler used to generate the PIC code was MikroC. [8].

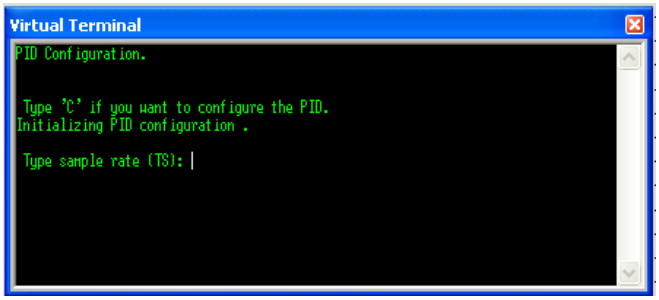

Figure 7 – PID configuration mode.

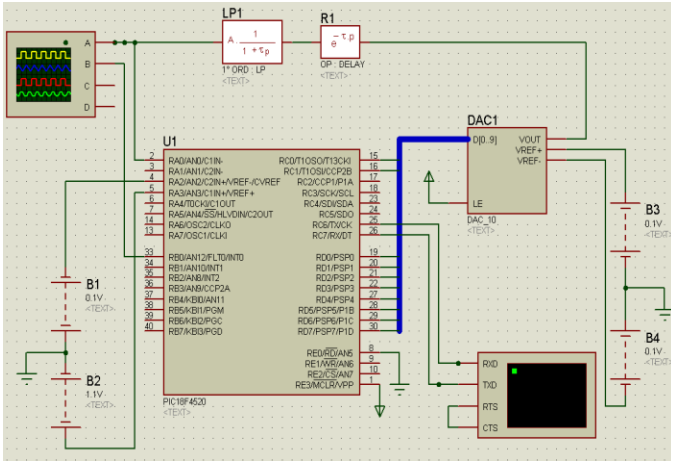

Figure 8. PID Proteus implementation using a microcontroller PIC18F4520.

V. Conclusion

The tests and simulations conducted by the implemented control system, using the bank of controllers, were satisfactory, regulating the pressure of any generated patient and satisfying all the restrictions established in the literature.

This work also enabled the study of digital controllers in microcontrollers, and although the environment Proteus is a simulation environment, the way to work with the components provides a practical overview of the implementation of the physical system. Furthermore, the results provided by Proteus environment are closer to the real implementation because a particular model of microcontroller is used.

After obtaining and validating the results presented here, other options for the embedded system will, still, be tested in the future as FPGA and DSP, and thus, their performances can be compared.

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