SOFTWARE FOR EMBEDDED CONTROLLER DESIGN
Application in Air and Water Caloric Electronystagmographic Stimulators

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Abstract: This paper describes the development and tests of a software which was projected to support the work of designing and testing dedicated embedded controllers. It was developed to accomplish two main features: helping to model the physical system to be controlled; and helping to easily implement and test a proposed controller to be applied to the physical system. Two practical applications are presented. The first one is the design of a temperature controller for a new version of a water caloric stimulator named E96, which has as main requirement fast and accurate temperature response with no overshoot. The second one is also a caloric stimulator, but the transfer media is air instead of water. Those equipments help otorhinolaryngologists in electronystagmography exam. Details on the caloric stimulators hardware and software, the proposed controllers and the results, are presented. The software was considered functional for the proposed applications.

1 INTRODUCTION

Digital control of a physical system, or plant, can be accomplished using a computer with internal software containing the algorithm that controls, through D/A conversion, the plant input variable. Closed-loop digital control requires the measurement and A/D conversion of the plant output variable. Many different kinds of digital controllers can be used for controlling different physical plants with the most variable range of requirements. Examples of requirements are the percent overshoot and the settling time for the step response of the plant (Dorf, 2001). Prior to the controller design is the modeling of the plant, which requires a modeling technique using, for example, the graphical analysis of the open-loop step response of the plant (Coelho, 2004).

The main motivation for the developed software PACD (*Plataforma para Aplicação de Controladores Digitais*, Digital Controllers Application Platform) was to create a software that, with the aid of an already existent hardware, would help modelling a physical system to be controlled, and additionally help designing a suitable controller for it, which would be validated through real tests. Such an ensemble of software and hardware would be helpful for designing and testing dedicated controllers, which later can be executed from microcontrollers or general purpose low cost DSPs, attempting to develop embedded dedicated controllers. The first practical application of the software PACD was to design temperature controllers in two electro-medical equipments.

Human corporal equilibrium comes from the interaction of three main systems: vision, proprioceptive system and vestibular system. Vestibular-Ocular Reflex (VOR) is responsible for vision focus during head movements (Castagno, 1994). Otorhinolaryngologists use several stimuli to diagnose diseases in the equilibrium systems. Caloric stimulus caused by the irrigation of heated water or air in the auditory conduit cause in healthy patient reflex ocular movements named nystagmus. The electric register of the ocular movements is called electronystagmography (ENG). The first Brazilian computerized system for ENG resulted from the joint work of Catholic University of Pelotas, Dr. Castagno Clinic and Contronic Sistemas Automáticos (Castagno, 1993; Costa, 1995). A

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caloric water stimulator named E96, shown in Figure 1 was developed for use during ENG exam, maintaining two water containers at different temperatures. A caloric air stimulator named E107, shown in Figure 2, was recently developed. Two main advantages of the air stimulator are causing less discomfort and allowing the exam in patients with tympanic perforation (Brookler, 2002).

Figure 1: Water caloric stimulator model E96.

Figure 2: Air caloric stimulator model E107.

2 MATHERIALS AND METHODS

2.1 PACD Software

The PACD software was created in C language, under Borland IDE C++ Builder 6. Its initial form presents two operating conditions: modeling or control. Each one includes its own graphical interface. In modeling operating condition, the plant is modeled using a step excitation signal and verifying its time response. Figure 3 presents the modeling interface, which is divided in 3 regions, enumerated in the figure as "1", "2" and "3". In the first region, it is possible to choose the step response modeling method while the second one is used to set the amplitude of the step heating power input, and to set the desired air flow. The third region shows the step temperature response. The horizontal axis shows essay time in seconds. As far as last the essay, this axis keep adjusting to show all essay time range. Vertical axis shows water/air temperature in Celsius degrees (ºC). The available step response modeling methods in PACD allow first order or second order models with or without time delay. Modeling method can be chosen between Ziegler-Nichols, Hägglund and Mollenkamp methods, as presented in Coelho (2004).

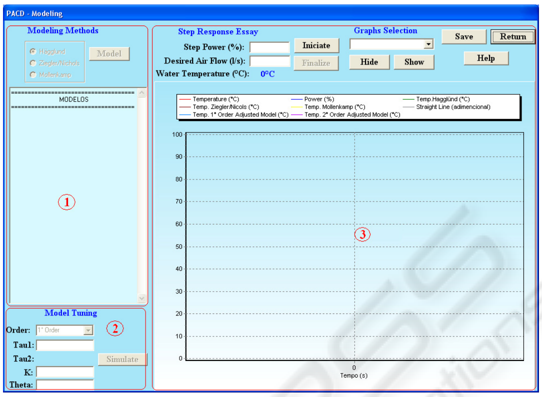

Figure 3: PACD modelling interface.

The control interface, shown in Figure 4, is also divided in three regions. In the first one it is possible to choose the controller type, to insert controller parameters and to command the compilation of the program with the chosen controller or controllers. The second region shows all chosen controllers and their parameters. In the third region it is possible to set the desired water/air temperature, the desired air flow and to start and stop controlling the plant. During the control operation, real water/air temperature in ºC is graphically shown against time in seconds. Horizontal axis is auto-adjustable. Real-time water/air temperature is shown numerically, as well as the difference between the desired temperature and the real one, named error. The control signal is also showed in the same graphic display, from 0% to 100% of the maximum possible power, or -100% to +100% in air equipment.

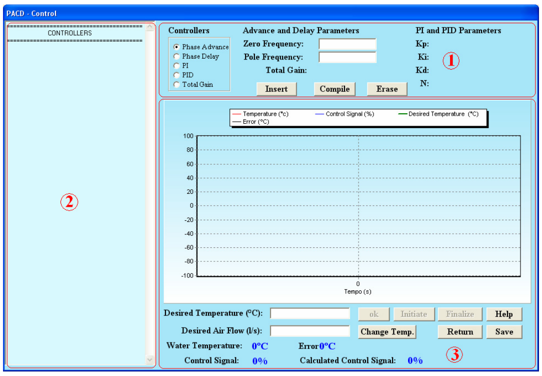

Figure 4: PACD control interface.

The main feature of this interface is the possibility of implementing and monitoring digital controllers in a fast and easy way. As a new essay will be done, different tuning parameters can be chosen and different cascade controllers can be appended. PACD current available controllers include lead, lag, lead-lag, double-lead, double-lag, PI and PID. The internal structure of PACD uses negative unitary feedback, and it allows to cascade up to 10 controllers of each type. This feature makes it possible to accomplish many different configurations to analyze in different operation essays, so that the controller designer can choose the configuration that gives the best results in terms of the desired plant operation requirements.

2.2 Water Test Setup

A testing setup was assembled, whose main parts are shown in the block diagram shown in Figure 5. The setup is composed by a printed circuit board from E96 equipment, a water container with a heater resistance inside and an additional serial communication interface. The used microcontroller is the Intel's N87C196KB running at 12 MHz. The temperature sensor is LM35DZ (National), accompanied by an amplifier and adjustment trimmer, allowing an adjusted error of 0.2 ºC in the whole temperature range, from 0 ºC to 50 ºC. A special version of the E96 embedded software was created (C language, IAR compiler), so the equipment is commanded through serial communication by PACD software in the external PC. The power control variable is delivered to a heater resistance of 700 W (220 V), and variable percent power is determined by PWM (Pulse Width Modulation) using integral cycle technique, in order to avoid harmonic frequencies in the mains. The PWM period corresponds to 50 cycles of the 60 Hz electric network, so the power driver has 2% resolution.

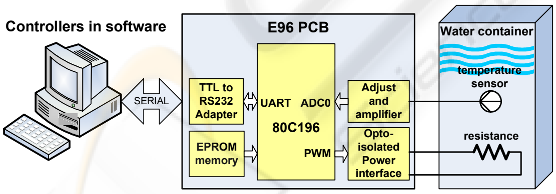

Figure 5: Water caloric setup block diagram.

2.3 Air Test Hardware and Software

Air stimulator E107AR was used with a modified protocol to facilitate the tests, and its basic block diagram is shown in Figure 6. The main parts of the system are composed by: an ADuC841 microcontroller (Analog Devices) running at 20 MHz; a precision resistive NTC sensor used to measure the temperature of the heated or cooled air flow, that after being adjusted by software, provides 0.2 ºC error in the whole temperature range (12 ºC to 50 ºC); an air pump that provides air flow from 4 to 12 liters/minute; and an air heater/cooler module formed by refrigeration sink, a Peltier effect device and a heater/cooler sink.

The internal E107AR software was modified to inhibit the original temperature controller and the periodic temperature sampling. It makes possible to PC software setting the sampling frequency as desired, and also, letting the PC software to control the output air flow and the amount of power to heat or to cool the air. The air pump power interface uses an AC current control technique that delivers AC voltage to the pump according to the microcontroller's D/A converter. The Peltier effect device is driven by an H-Bridge DC power interface, which is controlled by the ADuC841 pulse width modulation (PWM) output. The E107AR also has a built-in RS232 level converter to translate the microcontroller's TTL serial signals to ± 12 V levels on the PC serial port.

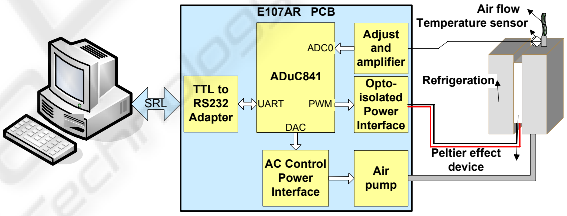

Figure 6: Air caloric setup block diagram.

3 RESULTS

Several tests were accomplished for PACD software validation and to find the best controller for each setup.

3.1 Results from Water Test Setup

For modeling the water temperature system to be controlled, a 25 % power step response was applied and three PACD available model methods where used. Figure 7 shows setup real step response pointed as "A". The letters B, C and D indicate respectively the responses from Hägglund, Ziegler-Nichols and Mollenkamp models. Carrying out a manual adjustment in Ziegler-Nichols obtained model, it was possible to arrive to the time response indicated by "E", which is even closer to the real plant time response. Equation 1 shows this model.

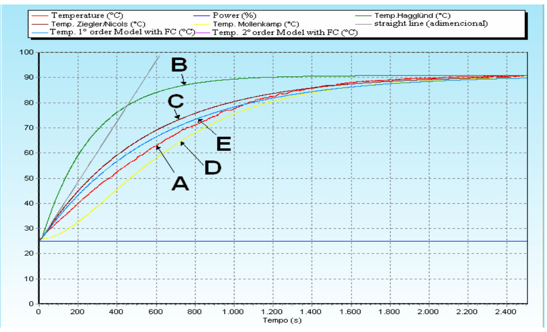

Figure 7: Water plant and models step response.

$$G(s) = \frac{2.592}{600\,s + 1} e^{-14s} \qquad (1)$$

Based on the selected model, several controllers were projected and tested according to classical control techniques (Dorf, 2001). The desired temperature was 44 °C and the initial temperature was 25 °C. An excellent step response of a controller using a cascade of phase-lead and PI compensators is shown in Figure 8, achieving 0% percent overshoot, 100 seconds settling time and ± 0.1 ºC stationary error.

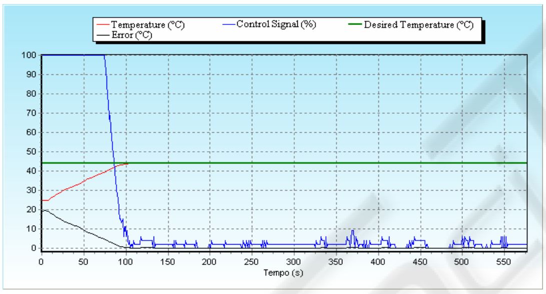

Figure 8: Water phase-lead + PI controller.

3.2 Results from Air Test Setup

Modeling the system from a 25 % power step input, it was obtained the model shown in Equation 2.

$$G(s) = \frac{0.1528}{250s + 1} e^{-3s} \qquad (2)$$

In all tests the desired temperature was 44 °C and the initial temperature was 25 °C, with 12 l/min air flow. After testing several developed controllers, the best step response was obtained from a cascade of phase-lead and PI compensators. Figure 9 shows this result, which achieved 1.80 % overshoot (0.34ºC), 45 seconds settling time and ± 0.31 ºC stationary error.

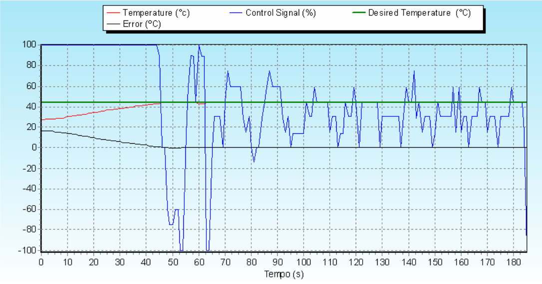

Figure 9: Air phase-lead + PI controller.

4 CONCLUSIONS

Analysing both water and air step responses achieved from cascade phase-lead and PI compensators, the responses where much better than the required results, which where set to 0.5 ºC maximum overshoot, 180 seconds of settling time and ± 0.5 ºC stationary error. This way, the PACD software was considered effective for the proposed applications, allowing the model construction and testing of several controllers, so helping to determine a better choice for the final controller. In the future, PACD will be improved to support other modelling methods and control strategies, such as adaptive control.

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