Temperature Acquisition and Control System based on the Arduino

M. A. Zermani, Elyes Feki, Abdelkader Mami

Abstract— ***Our work presents a low-cost temperature acquisition, for incubator system, based on the Arduino hardware platform; both the hardware and software components are detailed, together with experimental evaluation. This system was designed to facilitate the process of identification and control of a temperature of premature infant incubator. The experimental evaluation revealed that this system is not only capable of temperature signal acquisition, for incubator purposes, but it can also be used as a generic platform for other biomedical applications, greatly extending its applicability. In this paper we describe the proposed platform, with special emphasis on the design principles and functionality. System identification results based on least squares algorithm (RLS) to find the ARMAX input-output mathematical model. We opted for the GPC structure for control temperature. The results of implementation in real time on the neonatal incubator were presented and interpreted.***

Index Terms— ***Arduino, Temperature, Incubator, GPC controller***

I. INTRODUCTION

The first moments in the life of a premature newborn may be critical if he is exposed to an unprotected environment outside the womb. The Premature newborn is homoeothermic, but over a long period of time, he cannot maintain the thermal processes. The energy he provides is used in the following order of priority: for the functioning of vital organs, for thermoregulation and for growth. So we must provide a healthful hydrothermal environment to decrease the risk of body hypo- or hyperthermia for neonate [1][2]. Temperature acquisition has been a topic of increasingly growing development, since it constitutes the basis for diagnostic systems, and contributes to a better understanding of the body functions. The main objective of our work was to develop a low-cost acquisition system, capable to predict the system behavior and to obtain a model for the control algorithm synthesis. There are multiple hardware choices available, however the Arduino is currently the most flexible and easy-to-use hardware and embedded software platform m, with low cost, easy communication, and software running on a computer or other devices. Our goal was to communicate the Arduino board with the MATLAB 7.X software. The first use of our acquisition system targets the integration in a incubator platform, allowing real-time identification. However, it can be extended to numerous other important applications, depending on which signal are to be acquired. Nowadays, the use of the Arduino in medical and health applications has been widely explored for simple usage scenarios.

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One particular example is available at (Medicarduino, 2012), where the Arduino is used to acquire EEG signals, measure pulse, detect alcohol levels, and many other examples [3][4][5]. Proportional Integral Differential PID control has been widely used in infant-incubator applications for decades. This may stem from its relative simplicity. A great number of studies on this topic have been appeared in the literature [6]. A major disadvantage of the conventional control techniques is their inability to compensate interactions, when they are used in MIMO systems and their difficulty method for dynamic controller tuning. Generalized predictive control [7] appears to be attractive [8, 9]. In section II, we present an overview of the acquisition system based on Arduino board that designed especially for temperature data collection. The hardware, firmware, and software are detailed. In section III a theoretical modeling of the infant-incubator system will be developed. In section IV, the GPC control for the incubator is described. In section V, computer simulations will be conducted to review the feasibility and effectiveness of the proposed method. Finally, Section VI outlines the main conclusions and future work.

II. SYSTEM ARCHITECTURE

The proposed acquisition system has two main parts: Hardware and Software. In this particular work, the hardware is composed by the Arduino platform, incubator process and LM35 sensor. The different parts of the system are shown in the following Fig.1. The incubator is installed in a room which has a constant temperature and with protection from solar radiation. Regarding the software, there are two main programs developed: the Arduino Firmware, which controls its operation, and an Application Programming Interface (API) in MATLAB, which communicates with the Arduino controls, the acquisition process, and allows the access to the collected raw data. These two parts of the system will be detailed in the next sections.

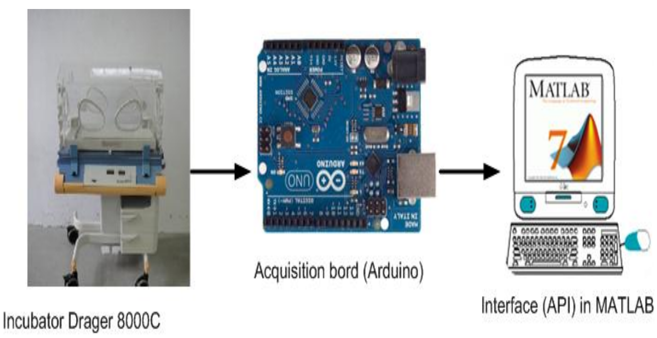

Fig. 1: Diagram of the Android Incubator Platform

A. Hardware

The main component of this section is the Arduino. Figure 2 shows the final prototype, with

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main components: The Arduino Uno is a microcontroller board based on the ATmega328 It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Uno differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega8U2 programmed as a USB-to-serial converter.

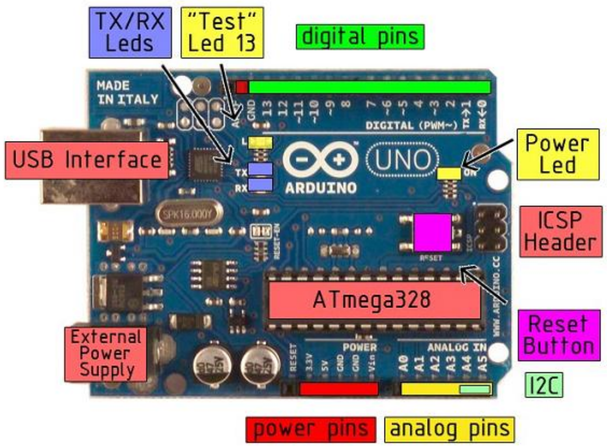

Fig. 2: Arduino Uno Prototype

B. Firmware

The firmware development performed in our work was designed to define the behavior of the Arduino microcontroller, setting its parameters such as sampling rate, and baud rate and communication protocol. The main purpose of the firmware is to control the analog and digital acquisition, using a pre-defined sampling rate; all the data acquired is sent to another device via USB connection. The open source Arduino environment makes it easy to write code and upload it to the I/O board, which is one of the main reasons why this platform was chosen as the base for our system. In figures. 3 represent the Programming Interface (API) developed in MATLAB software, which communicates with the Arduino controls, the acquisition process, and allows the access to the collected raw data.

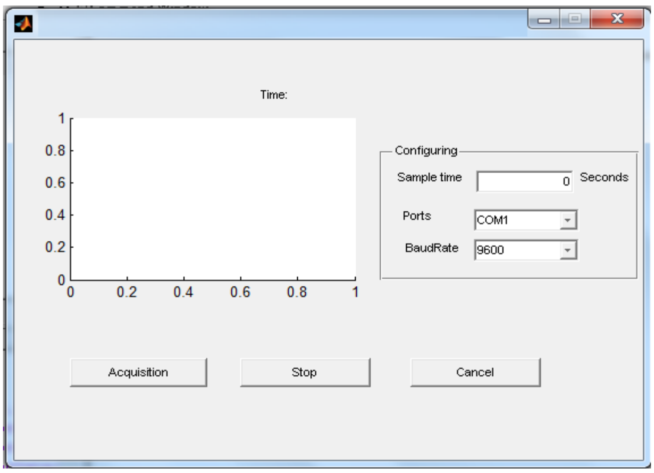

Fig. 3: Programming Interface (API) Developed in MATLAB Software

III. MODEL INCUBATOR

A. Method

Generally, there are three categories of models that can be used to simulate and predict the incubator environment. The first category is based on the concept of energy and mass balance (Taweel and Amer, 2006; Tourneux et al ., 2009)[6,10]. The drawback of this method is that these models are difficult to put in practice. The second category is based on the combination of physical and a mathematical model with prior knowledge of the system is necessary. The third category is based on computation intelligence such as fuzzy clustering, artificial neural networks and genetic algorithm. Oliveira et al . (2005)[11] used orthogonal basis functions to model the neonatal incubator prototype and Abbas and Leonhard (2009) al.[12] used a system identification of neonatal incubator based on adaptive ARMAX Technique. In this section an identification procedure for the newborn incubator is achieved and a linear model is computed. Although temperature characteristic is a continuous variable, it was measured and registered at time steps. In this discrete domain, the incubator system can be modeled in several ways, such as auto regressive models..

$$y(k) = -a_1 y(k-1) \ldots - a_n y(k-n) + \\ -b_{1u} y(k-1-d) \ldots + b_{mu} u(k-m-d) + e(k) \quad (2)$$

with d: delay, u: input system, y: output system and e: white noise. PRBS (pseudo-random binary sequence) signals were designed as input u(k) and the temperature was designed as output y(k). All experimental data were recorded with a sampling period of 10second. The selection of the appropriate orders of the ARMAX model is crucial and it has been performed by using AIC (Akaike Information Criterion) in the conventional and standard approach (Fukata *et al.*, 2006).[13] The parameters of the ARMAX model were updated on line using ERLS (Extended Recursive Least Square) method (Landau *et al.*, 2006)[14]. The identification of a parametric system is to determine experimentally from measurements of input-output coefficients called parameters. The parametric identification methods are numerous. In this work, we apply the approach of recursive least squares that can be described by the following equations.

$$P(k) = \frac{1}{\lambda_1(k)}\left[P(k-1) - \frac{P(k-1)\varphi(k)\varphi^T(k)P(k-1)}{\frac{\lambda_1(k)}{\lambda_2(k)} + \varphi(k)\varphi^T(k)P(k-1)}\right] \quad (3)$$

$$K(k) = P(k)\varphi(k) \quad (4)$$

$$\theta(k) = \theta(k-1) + K(k)y(k) - \varphi(k)^T\theta(k-1) \quad (5)$$

θ is a vector of parameters to be identified and '(k) is an observation vector which are given by:

$$\theta^T = [a_1, a_1 \ldots a_m b_1, b_2, \ldots b_n] \quad (6)$$

$$\varphi^T(k) = [-y(k-1), -y(k-2) \ldots - y(k-n) \\ u(k-1-d) \ldots u(k-d-m) \quad (7)$$

The algorithm with constant forgetting factor is to choose $\lambda_1(k) = \lambda_1 1$ and $\lambda_2(k) = 1$, typical values for _1 is selected within an interval [0.95, . . . , 0.99]. The

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effect of λ_1 is to introduce a decreasing weight on the previous data. This is why _1 is known as the forgetting factor. The maximum weight is given to the most recent error. This type of profile suits the identification of slowly time varying systems (Landau *et al*., 2006)[14]. To excite the heating resistance of the incubator, we used a ON OFF sequence. This sequence is generated programmatically. After several trials, we found that the dynamic of warming is much faster than cooling. Thus, we were forced to extend the sequence a little cooling. The response from the incubator to the excitation is shown in Fig. 4.

B. Experimental Evaluation

Identifying parameters of a NARMA model is generally produced as flows: this problem persists in the implementation of a protocol adapted to the experimental method to collect relevant data. In fact, the quality of the results of identification depends on the acquisition of data of the input-output data sampled around a working point. PRBS (Pseudo Random Binary Sequence) is designed as input signal based on preliminary experiments. These high frequency signals, allow to excite all the vibration. All experimental data were recorded with sampling frequency of 0.1 Hz.

C. Validation of the Method

To evaluate the quality of the identification procedure used, it is necessary to complete the identification process by verifying if the obtained behavior pattern is satisfactory. Fig. 8 represents the evolution of the temperature measured inside the incubator and the temperature estimated by chosen the model depending on the command used .

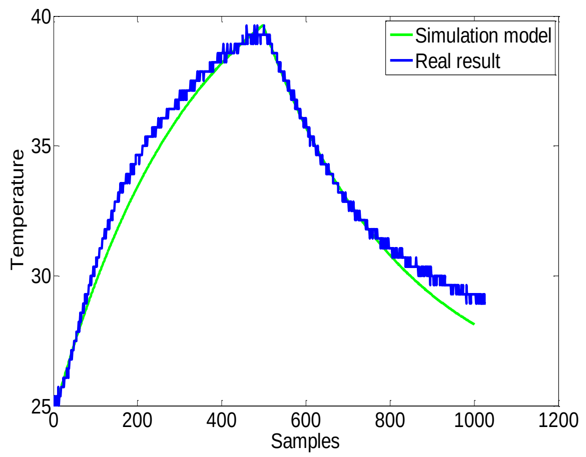


Fig. 4: Real and Estimated Temperature

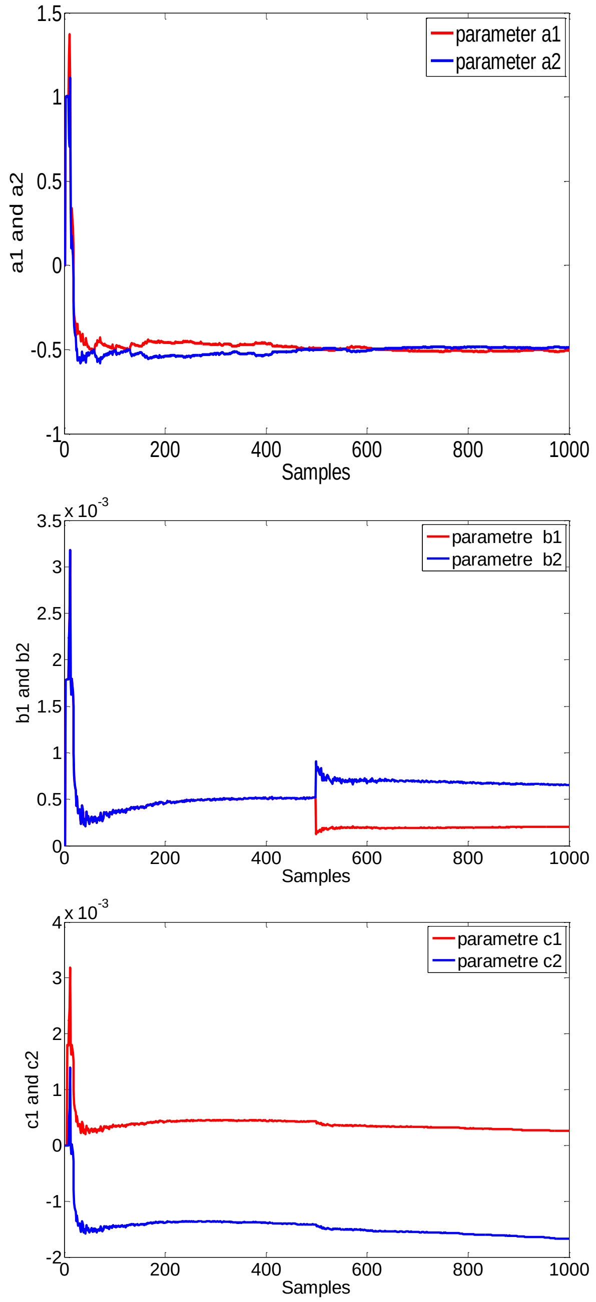


Fig. 5: Represents the Evolution of Estimated Parameters

The model developed is written as follows:

$$y(k) = 0.5057y(k-1) + 0.4897y(k-2) + 2.0540e-04u(k-3) + 6.5348e-04u(k-4) + e(k) + 2.5786e-04e(k-1) - 0.0017e(k-2) \quad (8)$$

IV. PREDICTIVE CONTROL

Having established the number of compartments as two, we turn our attention to a more detailed description of the generalized predictive control (GPC) system. The GPC based on the minimization of a quadratic criterion on a sliding horizon, which involves a term related to the difference between the predicted output sequence and the sequence of future control [7]. The criterion is given by the following relation:

$$J_i = \lambda_{yi} \sum_{t=N_i}^{HP_i} [y_{C_i}(k+t) - \hat{y}_i(k+t)]^2 + \lambda_{ui} \sum_{t=1}^{N_{C_i}} \Delta u_i^2(k+t-1) \quad (9)$$

With:

$\hat{y}_i(k)$: the output value predicted at time k,

$y_{C_i}(k)$: the set points values at time k,

$\Delta u_i(k)$: the increment of control at time k,

N_i : the minimum prediction horizon,

HP_i : the maximum prediction horizon,

N_{C_i} : the control horizon,

λ_{ui} : the control-weighting factor.

λ_{yi} : the error weighting factor.

A. *Prediction of the System Output*

The approach of generalized predictive control is based on a dynamic model of type CARIMA (Controlled. Auto-Regressive Integrated Moving Average), given by the following form:

$$A_i(z^{-1})y_i(k) = z^{-d_i} B_i(z^{-1})u_i(k-1) + C_i(z^{-1})\frac{\xi_i(k)}{\Delta(z^{-1})} \quad (10)$$

With $\Delta(z^{-1}) = 1 - z^{-1}$ corresponds to an integral action.

Using (10), the output at time (k+t) will be:

$$y_i(k+t) = \frac{B_i(z^{-1})}{A_i(z^{-1})}u_i(k+t-d_i-1) + \frac{C_i(z^{-1})}{A_i(z^{-1})\Delta(z^{-1})}\xi_i(k+t) \quad (11)$$

By applying the Euclidean algorithm on the second term of (11), we get:

$$\frac{C_i(z^{-1})}{A_i(z^{-1})\Delta(z^{-1})} = L_t(z^{-1}) + z^{-1}\frac{G_t(z^{-1})}{A_i(z^{-1})\Delta(z^{-1})} \quad (12)$$

Using (11) and (12) and we assuming that the term related to the disturbance is zero, the optimal predictor of the output is written as follows:

$$\hat{y}_i(k+t) = \frac{L_t(z^{-1})B_i(z^{-1})\Delta(z^{-1})}{C_i(z^{-1})}u_i(k+t-d_i-1) + \frac{G_t(z^{-1})}{C_i(z^{-1})}y_i(k) \quad (13)$$

A second Diophantine equation decompose the predictor in two terms: a first term based on the current output, old orders, the system output and a second term dependent on future orders.

$$\frac{\sigma_i(z^{-1})}{C_i(z^{-1})} = H_t(z^{-1}) + z^{-t+d}\frac{R_t(z^{-1})}{C_i(z^{-1})} \quad (14)$$

With:

$$\sigma_i(z^{-1}) = L_t(z^{-1})B_i(z^{-1}) \quad (15)$$

The optimal predictor of the output is written as follows:

$$\hat{y}_i(k+t) = H_t(z^{-1})\Delta(z^{-1})u_i(k+t-d_i-1) + \frac{G_t(z^{-1})}{C_i(z^{-1})}y_i(k) + \frac{R_t(z^{-1})}{C_i(z^{-1})}\Delta(z^{-1})u_i(k-1) \quad (16)$$

Where: $H_t(z^{-1})$, $G_t(z^{-1})$, $R_t(z^{-1})$ et $L_t(z^{-1})$ are polynomial solutions to the Diophantine equations [8].
The matrix formulation is represented as follows:

$$\hat{Y}_i(k) = \hat{H}\Delta U_i(k) + \frac{\hat{G}(k)Y_i(k)}{C_i(z^{-1})} + \frac{\hat{R}\Delta U_i(k-1)}{C_i(z^{-1})} \quad (17)$$

With:

$$\Delta U_i = [\Delta u_i(k) \cdots \Delta u_i(k+N_{C_i}-1)]^T \quad (18)$$

$$\hat{G} = [G_{1+d_i}(z^{-1}) \cdots G_{HP_i+d_i}(z^{-1})]^T \quad (19)$$

$$\hat{R} = [R_{1+d_i}(z^{-1}) \cdots R_{HP_i+d_i}(z^{-1})]^T \quad (20)$$

$$\hat{H} = \begin{pmatrix} h_0 & 0 & \cdots & 0 \\ h_1 & h_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ h_{HP_i-1} & h_{HP_i-2} & \cdots & h_{HP_i-N_{Ci}} \end{pmatrix} \quad (21)$$

B. *The Predictive Control Law*

We can write the criterion J in matrix form:

$$J_i = [\hat{Y}_i(k) - Y_{C_i}(k)]^T \chi_i [\hat{Y}_i(k) - Y_{C_i}(k)] + \lambda_{ui}\Delta U_i(k)^T \Delta U_i(k) \quad (22)$$

With: $Y_{Ci} = [y_{C_i}(k+N_i+d_i) \cdots y_{Ci}(k+HP_i+d_i)]$ (23)

The optimal control law is derived from analytical minimization of the previous cost function. Only the first control value is finally applied to the system.

$$u_i(k) = u_i(k-1) + m_{GPC_i}^T [Y_{Ci}(k) - \frac{\hat{G}(k)Y_i(k) + \hat{R}\Delta U_i(k-1)}{C_i(z^{-1})}] \quad (24)$$

Which: $m_{GPC\,i}^T$ represents the first line of $(\hat{H}^T\chi_i\hat{H} + \lambda_{ui}I_{N_{Ci}})^{-1}\hat{H}^T$ and $I_{N_{C_i}}$ is diagonal matrix of size $N_{Ci} * N_{Ci}$ and χ_i is diagonal matrix of size $HP_i * HP_i$

$$\chi_i = \begin{pmatrix} \lambda_{yi} & & 0 \\ & \ddots & \\ 0 & & \lambda_{yi} \end{pmatrix} \quad I_{N_{Ci}} = \begin{pmatrix} 1 & & 0 \\ & \ddots & \\ 0 & & 1 \end{pmatrix} \quad (25)$$

We can express constraint on the process in the form:

$$u_{\min} \le u_i(k) \le u_{\max}$$
$$-\Delta u_s \le \Delta u_i(k) \le \Delta u_s \qquad (26)$$

For the systems with constrains on the controller output value, on the controller increment output value or on the system output value, the vector Δu is calculated by function FMINCON of Optimization Toolbox of the language Matlab.

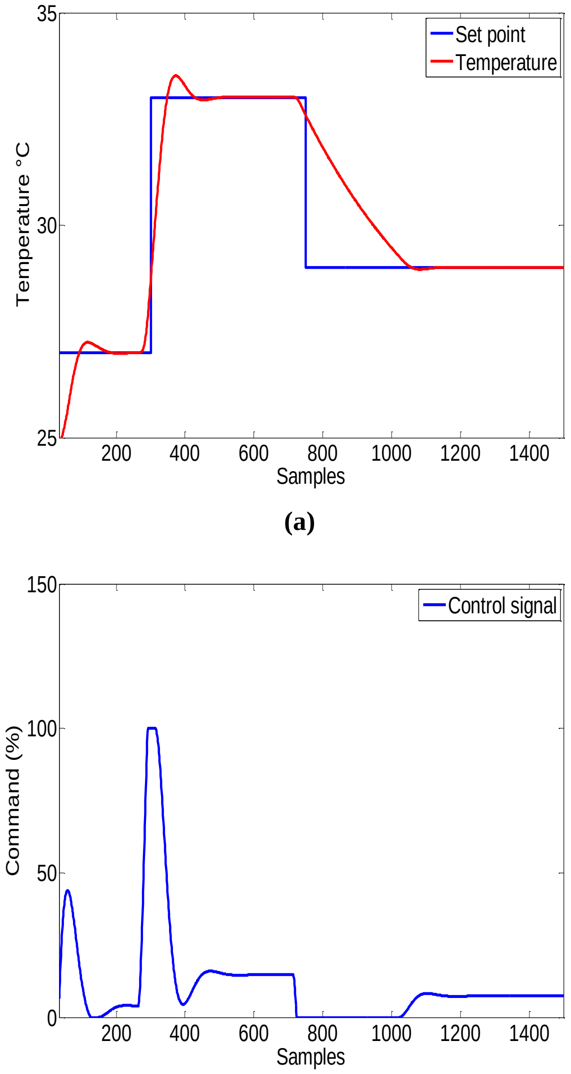
V. RESULTS

The temperature controller is constructed using the model identified in section III. The performance of the GPC control strategies is given in Fig. 6 and Fig. 7. These figures show that the controller is able to keep the internal temperature close to the desired value. Fig. 7(a) presents the temperature controller's behavior. The situation described here is the heating phase and the regulatory control around 33C. During the interval [28°C,38°C] sampled, the hand ports incubator was opened and the internal temperature initially dropped then recovered the optimal value. The main advantage of the proposed control law is the regulatory behavior, with small deviations around the steady state value

To check the feasibility of the proposed approach control, the principal parameters are shown in table 2:

Controller	HP	Nc	λ_u	λ_y	constraints
GPC1	20	1	0.2422	1	$0 \le U_1 \le 100$ $-100 \le \Delta U_1 \le 100$

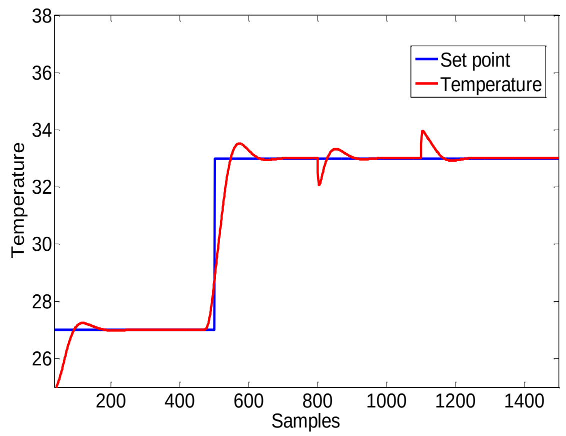
The most adequate value for the prediction horizons was calculated taking into account the values of the fundamental time constant and the sampling period used for control purposes. In this case prediction horizon was taken as $HP_1 = 20$, the choice of the range of variation of the control horizon is determined by the stability of the open loop system. However, the reasonable choice that provides a compromise between the degree of stability and performance is as follows: $HC \le HP$. Respecting this condition and based on the simulation results, control horizon was taken as $Nc_1 = Nc_2 = 1$. The choice of the weighting factors of the control increments are based on [8] $\lambda_{u1} = 0.2422$, . For the validation processes, the simulation time for system control is set to be four hours. The incubator air temperature is illustrated in figure 6. Initially, the air temperature starts at 25 °C, which is below the set temperature.



(a)

(b)

Fig. 6: Response of Incubator the Heating System Controlled by GPC Controller



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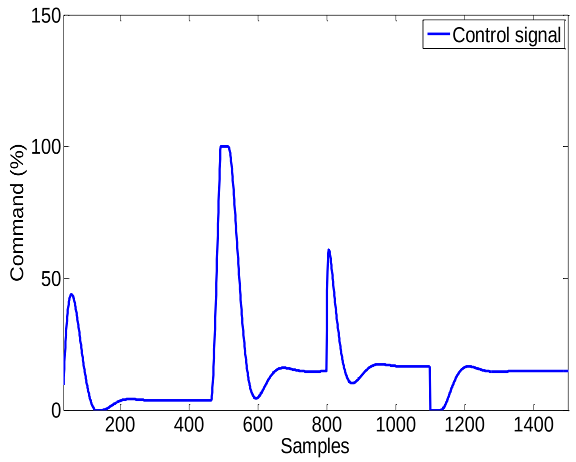

Fig. 7: Response of Incubator the Heating System Controlled by GPC Controller with Perturbation

VI. CONCLUSION

We have designed and implemented a first prototype of an temperature acquisition system for the incubator based on Arduino. Experimental results have shown that the data collected through the proposed system have two dynamic. We found that the dynamic of warming is much faster than cooling. Although this system was designed for identification and control temperature of neonatal incubator system, it can also be used to acquire other types of signals, becoming a more generic acquisition system. This work may be continued in several areas. Generalized Predictive Control (GPC) has made its test in controlling the air temperature inside the incubator. Nevertheless, the skin temperature is the most important variable should be adjust to minimize heat loss. The present model may be used as prediction model in GPC control strategy. Also, an adaptive model may be exploited This technique is very important to update the parameters model that depend on infant related parameters such size maturity level, metabolic factor, maturity of skin body development also for changing incubator characteristics

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