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Implementation of a Feedback I^2-Controlled Constant Temperature Environment Temperature Meter

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Abstract: A feedback thermo-resistive sensor-based measurement scheme was proposed to estimate physical quantities like solar radiation (H), fluid velocity (U) and environment temperature (T_a). It was implemented as an environment temperature meter, using PI controller. Controller implementation was done digitally using FPGA. Practical results are presented.

Keywords: Temperature measurement, Constant temperature, Feedback control.

Introduction

Negative feedback circuit configuration with a thermo-resistive sensor in one arm of Wheatstone bridge, used to estimate solar radiation and fluid velocity [4-8], has shown some performance limitations due to offset voltage [4]. In an alternative system presented, Figure (1), sensor temperature is maintained quit constant, using feedback control. The system is composed by two subsystems, one with a controller, and other with a sensor, in a classical feedback loop. *x(t)* is the measure variable, which is proportional to square sensor current (I_s^2), and *y(t)* is the observed variable, proportional to sensor resistance (R_s), which must be kept constant by controller action. If sensor resistance remains constant, sensor temperature (T_s) remains also constant and, any change over *x(t)* is a linear function of H or T_a variations [1-2]. An implementation of this system as an environment temperature meter was realized, (Fig. 3), and results are related.

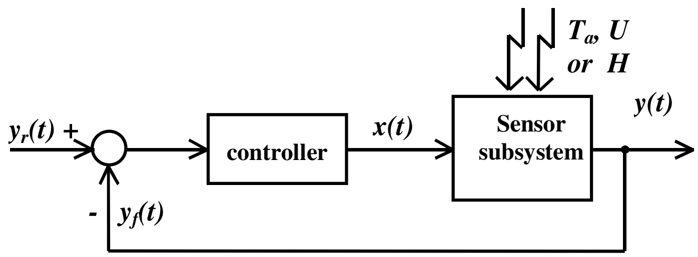

Figure 1. Feedback Control System

Formulation

Static analysis of the feedback system

Using the same methodology described for feedback I^2-controlled constant solar radiation meter [1], and applying to environment temperature meter, measure variable could be expressed as:

$$x = I_s^2 = R_s^{-1} hS(T_s - T_a) \tag{1}$$

With Rs being the sensor resistance, h the sensor heat transfer coefficient, S the sensor superficial area, T_s the sensor temperature and T_a the environment temperature.

Exciting sensor with PWM current pulse, equation (1) could be written as [3],

$$x = T_1 = \frac{T}{I_m^2} R_s^{-1} hS(T_s - T_a) \tag{2}$$

With T_1 the modulated pulse width, T the system control period and I_m the PWM current pulse amplitude.

Linear relationship between pulse width variations, the measure variable, and environment temperature, the variable to be estimated, was obtained [1-3].

Model of small signal of thermo-resistive sensor

The dynamic thermal equilibrium equation of sensor, (NTC thermo-resistive sensor), was linearized around a quiescent point (R_{so}, T_{so}). Laplace transformer was used to obtain sensor small signal transfer function [1]:

$$H(s) = \frac{Y(s)}{X(s)} = \frac{R_s(s)}{X(s)} = \frac{kx}{\tau_a.s + 1} \tag{3}$$

In which,

$$kx = \frac{R_{so}}{(hS.kt - X_o)}$$

$$\tau_a = \frac{mc.kt}{(hS.kt - X_o)}$$

$$kt = -\frac{T_{so}^2}{B.R_{so}}$$

With k_x being the function gain, τ_a the sensor apparent time constant and k_t the temperature coefficient.

Controller transfer function

PI controller was used to obtain a feedback system with a response time less then sensor constant time and s-domain function transfer is given by equation (4).

$$G(s) = \frac{Kp.s}{s} \quad (4)$$

Model of small signal of a thermo-resistive sensor-based feedback environment temperature meter

Feedback system scheme can be observed in Figure (2).

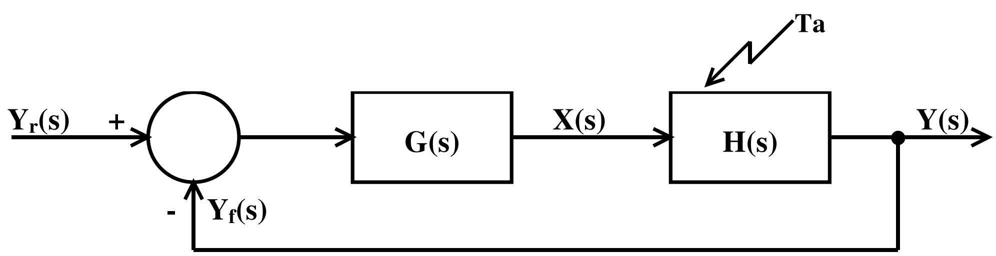

Figure 2. Analog feedback system

Using equations (3) and (4) we could get system transfer function using pole-zero cancellation:

$$\frac{Kp}{Ki} = \tau_a \qquad \text{(First project condition)}$$

$$T(s) = \frac{1}{\frac{s}{kx.Ki} + 1}$$

System transfer function had a pole at $-kx.Ki$ or a time constant of $\tau_{sr} = \frac{1}{kx.Ki}$

$$Ki = \frac{1}{kx.\tau_{sr}} \qquad \text{(Second project condition)}$$

Feedback system constant time, τ_{sr}, was chosen to be much less than sensor small model apparent constant time, τ_a, and much less than sensor intrinsic constant time, τ.

Conclusion

Feedback system dynamic behavior depends on controller parameters, which depends on sensor small model constant time, and sensor operation point. *x(t)* did not show the same excursion limitation as observed in conventional system output voltage.

This system was implemented for environment temperature measurement. The convergence to new reference levels was obtained as supposed.

The linear relationship between environment temperature and measure variable was possible due to PWM modulation of measure variable, after PI controller action, which could transform quadratic relationship between measure variable and observed variable into a linear one. This relationship simplifies compensation of T_a in anemometers and radiometers [8-9].

Series resistors absence with sensor should permit the use of lower power voltage, which is an actual tendency in design of integrated circuits.

Experimental

General

Controller system was implemented in FPGA, Figure (3), to permit higher working frequencies, and because digital dedicated systems improves performance to real time systems when compared to micro-processed systems. Numeric PI controller was based on analog PI controller and uses the same principle.

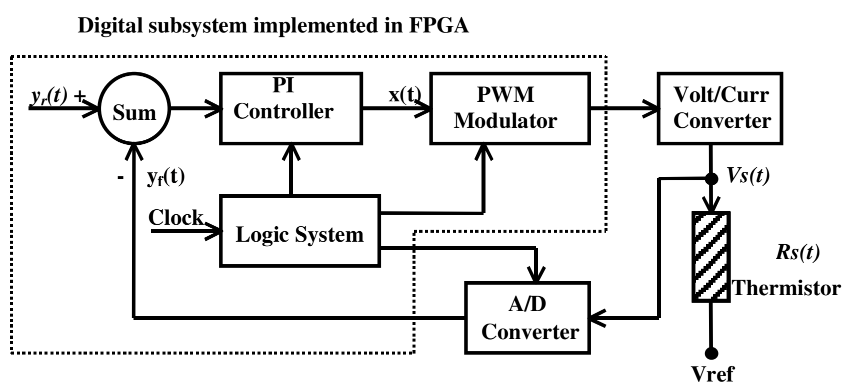

Figure 3. System implementation with FPGA

Thermo-resistive sensor transient response to a change on reference level is shown in Figure (4). Sensor temperature operation point was defined at T_{so} = 74 ^{o}C and it was suddenly changed to 80 ^{o}C. Sometime later to 68 ^{o}C and sometime later returned to original level of 74 ^{o}C. In this figure it can be observed that measured values converging to simulating references levels.

The linear relationship between environment temperature and measure variable can be observed in Figure (5). A linear approximation was realized and maximum difference between measured pulse width duration and straight line was equal to -2.2358.

Project Data

For a NTC thermo-resistive sensor with A = 5.9936e-2 Ω, B = 3423.3 K, ($R_s = Ae^{\frac{B}{T_s}}$), hS = 7.011e-4 W/K, mc = 1.4092e-3 J/K, τ = 2.01 s, sensor analog resistance reference R_{so} = 1149 Ω, sensor analog temperature reference T_{so} = 74 ^{o}C, I_{so} = 5.5733 mA, I_{mo} = 7.3552 mA, k_t = -3.0637e-2 K/Ω, k_x = -2.2908e7 Ω/A^2, τ_a = 0.861s, τ_{sr} = 0.1 s, analog PI controller constants K_p = -3.7575e-7 A^2/Ω and K_i = -4.3652e-7 A^2/(Ω.s), numeric PWM resolution n_{PWM} = 10 bits, Analog/Digital resolution n_{CAD} = 12 bits, numeric PI controller constants K_{pD} = -4 and K_{iD} = -5, numeric reference y_{rD} = 1762, $Clock$ = 1 MHz, T = 1.024 ms, T_{1o} = 50% T.

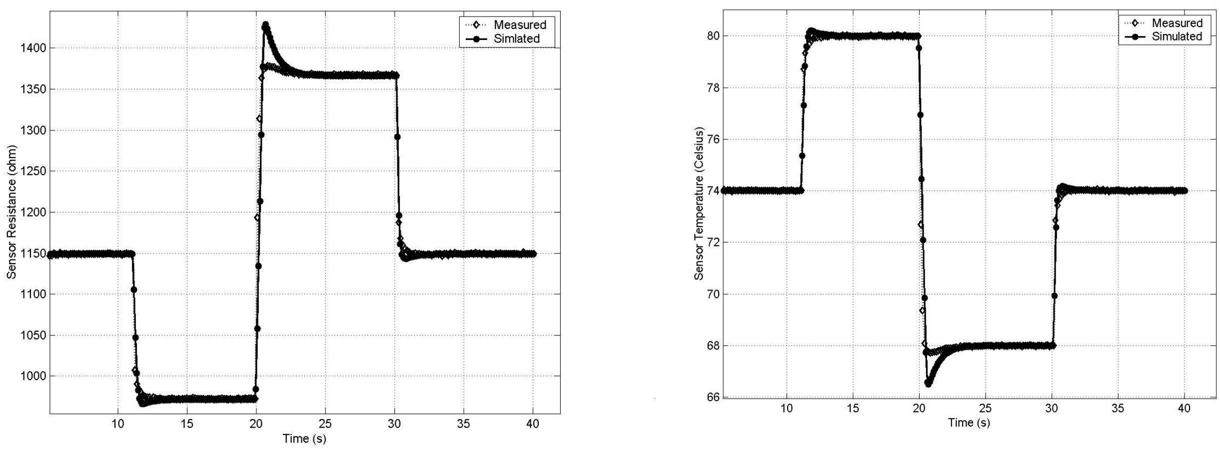

Figure 4. Thermo-resistive Sensor Response Time to a Sudden Change on Reference

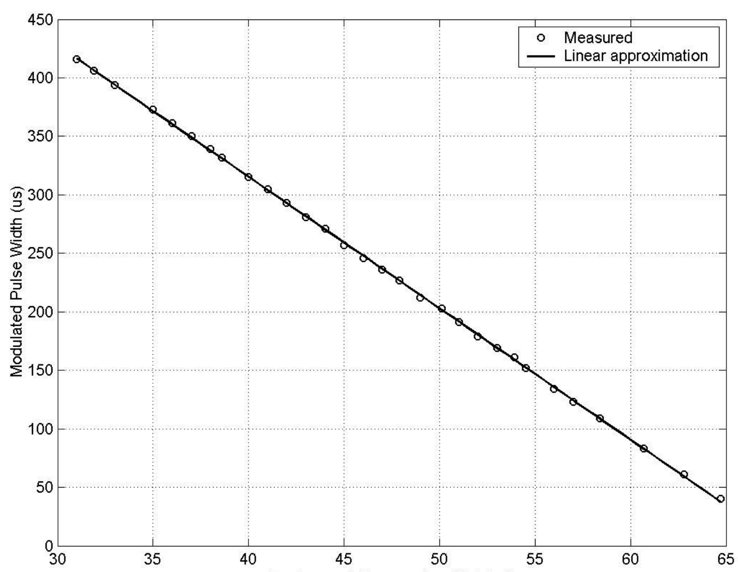

Figure 5. Linear Relationship Between Measure Variable (Pulse Duration) and Environment Temperature

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Sample Availability: Available from the authors.