

## An Embedded PID Temperature Control Scheme with Application in a Medical Microwave Radiometer

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### Abstract

Microwave radiometers are instruments for resolving blackbody radiation of heated matter above absolute zero, with many applications including breast cancer diagnosis. In this work a prototype microwave radiometer including a controllable noise reference generator was designed. The design of this noise source is based on the NC303 noise diode that delivers symmetrical white Gaussian noise and flat output power versus frequency (10MHz – 10GHz). An embedded PID control scheme is responsible for temperature stabilization of this sub-unit. The PID controller is designed to cope with disturbance rejection and set-point tracking problems. The first step in PID tuning involved extraction of the system's open loop transfer function. Then the internal model control (IMC) method was used for tuning the controller and the resulting control scheme was successfully applied to the real system.

*Keywords:* Automatic control, PID, Radiometer, Temperature control

### 1. Introduction

Microwave radiometers are instruments for resolving blackbody radiation of heated matter above absolute zero. The emission levels of blackbody radiation vary with frequency. Medical microwave radiometers are non-invasive, non-toxic, absolutely safe, and can be used to form a thermal image from the tissues of the human body. An application field of great interest for the microwave radiometer is the diagnosis of breast cancer.

The front-end of a conventional digital radiometer (e.g., a Dicke RF front-end) consists of an antenna, a noise reference, an electronic switch, a low noise amplifier, a band pass filter with appropriate Q factor, a booster amplifier, as well as additional components such as a square law power detector, a low frequency (LF) amplifier, an analog to digital converter (ADC), and a CPU controller. Given the principle of practical multi-stage cascaded radiometric systems, the noise performance of the first stage is critical. This inherent property is often utilized in measurement systems through implementation of low-noise preamplifiers close to the sensor element; furthermore, it leads to the postulate that achieving a high sensitivity requires a wide band implementation and large time integration, whereas a narrow band design is balanced by larger time integration.

### 2. Medical microwave radiometer

#### 2.1 Operating principles

Medical radiometers are able to provide temperature

distributions in hypodermic biological tissues when operated in the microwave spectrum. Nevertheless, an important limitation of the microwave radiometric observation principle is the ultra-low signal level of the thermal noise emitted by the blackbody. The normal human body temperature of 37°C will give a power density of approximately -173.7dBm/Hz at the antenna input. For instance, by designing an RF front-end with a bandwidth (BW) of 500MHz, the power will increase to approximately -86.7dBm after integration. This weak power needs further amplification for possible detection. The selected power detector typically requires a signal level of -50dBm. In order to achieve this, a cascade of two amplifiers is needed. Special microwave design is required in order to eliminate oscillation or other instability problems.

#### 2.2 A prototype medical microwave radiometer

Our approach comprises of a compact (patch) single-element wideband antenna able to receive microwave signals in the frequency region from 1GHz to 4GHz. The antenna interfaces with a single channel Dicke microwave radiometer [1]. Figure 1 depicts a simplified block diagram of the designed microwave radiometer. In addition, a band pass filter selection circuit is responsible for the desired operating RF band, which corresponds into different penetrating depths inside the human tissue; hence providing a series of temperature measurements in succeeding depths.

This design allows reasonable penetrating depth and lateral spatial resolution [2]-[4], having the additional advantage of less electromagnetic interference within selected frequency bands, compared to other frequency ranges that contain cellular phones and wireless networks.

Frequency bands between 3GHz and 4GHz are also quiet bands [5]; on the other hand they provide smaller penetration depth in the human body compared to lower frequencies,

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even though they have been proven to be an adequate choice for detecting superficial breast cancer [6].

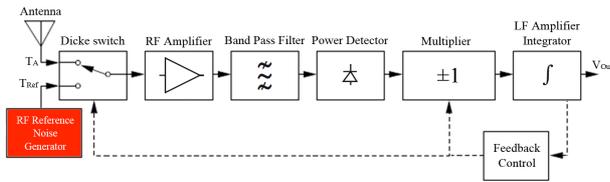


Fig. 1. Dicke radiometer

Specific operating RF bands are chosen, in order to achieve succeeding penetration depths in the human body and to have negligible electromagnetic interference.

In this work a prototype “RF Reference Noise Generator” was designed and implemented (Figure 2). This subunit is depicted with red color in Figure 1. The design of this noise source is based on the NC303 noise diode that delivers symmetrical white Gaussian noise and flat output power versus frequency (10MHz – 10GHz).

The thermal stabilization of the noise diode NC303, is of great importance for the reliable and stable operation of this “RF Reference Noise Generator”. This requirement led us to implement a special thermo-box for the housing of this circuit as depicted in Figures 3 and 4.

This thermo-box, in combination with the embedded PID controller (Figure 5) ensures that this “RF Reference Noise Generator” is operating in a thermal stabilized environment.



Fig. 2. RF Reference Noise Generator (10MHz – 10GHz)

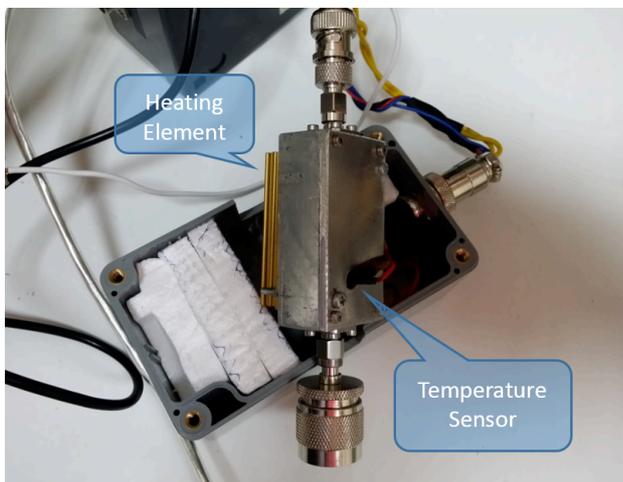


Fig. 3. Preliminary implementation of thermo-box (Inside view)

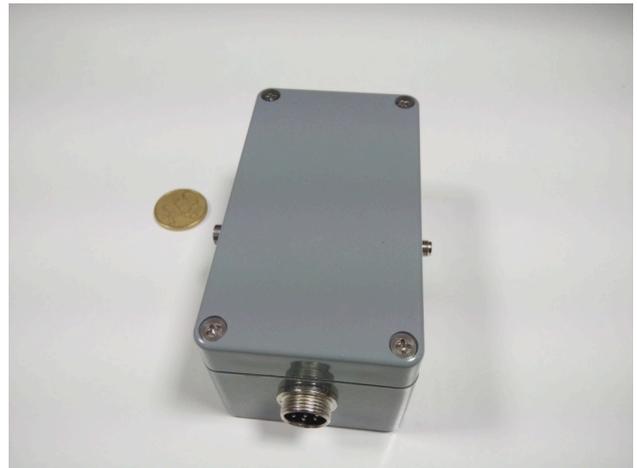


Fig. 4. Preliminary implementation of thermo-box (external view)

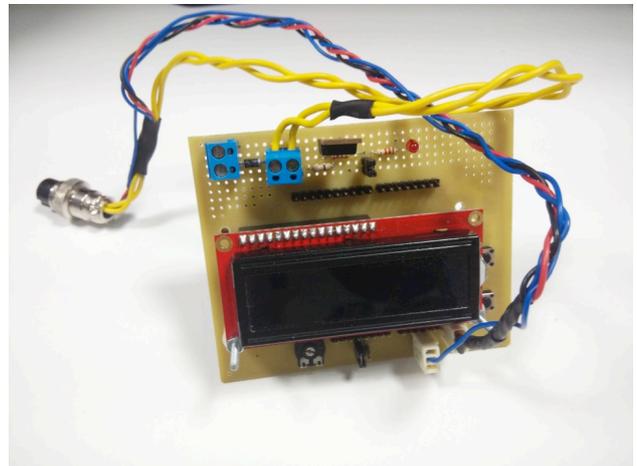


Fig. 5. Preliminary implementation of the embedded PID controller

In the following section the operation and tuning principles of the embedded PID controller are going to be presented.

### 3. PID temperature control scheme

A PID temperature control scheme is responsible for the temperature stabilization of the NC303 noise diode. The embedded PID controller is based on the 8-bit AVR microcontroller ATmega328P. Besides the PID controller and the NC303 noise diode, the closed loop responsible for temperature stabilization consists of a heating resistor acting as the final control element, and an embedded temperature sensor. The power delivered to the resistor is controlled by a pulse-width modulation (PWM) system. As far as the temperature sensor is concerned, an integrated, digital-output temperature sensor, featuring an incremental Delta-Sigma ADC with a two-wire interface that is compatible with the SMBus and I<sup>2</sup>C interfaces, is applied. The digital sensor offers four different resolutions to optimize between conversion time and sensor sensitivity. In this work, the maximum resolution of 14 bits was selected so that the sensor could sense even small changes in temperature. A schematic description of the closed loop control scheme can be seen in Figure 6.

#### 3.1. Tuning methodologies for PID

A PID controller has three terms: the proportional term (P) acts like a gain, multiplying the control error; the integral term (I) integrates the past control errors and thus helps to eliminate steady-state offset; the derivative term (D) takes into account the rate of change of the control error and helps to speed up the response and reduce oscillations. The transfer function of a PID controller in cascade form is given by:

$$G(s) = K_c \frac{\tau_I s + 1}{\tau_I s} (\tau_D s + 1) \quad (1)$$

where  $K_c$  is the controller gain and  $\tau_I$  and  $\tau_D$  are the integral and derivative times, respectively. Tuning of the PID controller is then equivalent to finding suitable values for these parameters, in order to optimize the closed loop response. Though PID tuning involves only three parameters, finding optimal values is not an easy task without using a systematic procedure.

A commonly used tuning procedure is the Ziegler-Nichols method [7]. The first step in this approach is to increase the gain using only P control until the system reaches marginal stability, exhibiting sustained oscillations. At this point, the ultimate gain  $K_u$  and the corresponding ultimate period  $P_u$  are measured. The three terms are then tuned using the values depicted in Table 1.

A different approach for tuning the PID controller is the internal model control (IMC) method [8]. This technique is based on approximating the process by a first or second-order system plus delay, by defining the following parameters:

- System gain  $K$
- Dominant time constant,  $\tau_1$
- Effective time delay,  $\theta$
- Second order time delay,  $\tau_2$

After identifying the aforementioned parameters, values for the PID terms are calculated using the third column of Table 1. The IMC method makes use of a tuning parameter  $\tau_c$ , where  $-\theta < \tau_c < \infty$ . Small values of  $\tau_c$  favor fast but oscillatory responses, whereas large values favor more stable, but slower responses [9].

## 4. Results and discussion

### 4.1. Open loop identification

Application of the IMC tuning method requires an approximation of the transfer function of the system under control. This is achieved by studying the open loop response after introducing a step change to the PWM. To be more specific, the diode temperature was allowed to reach a steady-state temperature of 26.16°C and at that point a step change from 0% to 16% was introduced to the PWM. Figure 7 depicts the open loop response to the step change. Based on the open loop response, the transfer function parameters shown in Table 2 were identified.

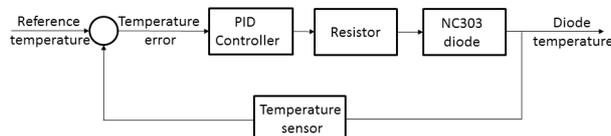


Fig. 6 Schematic description of the closed loop control scheme

### 4.2. Closed loop experiments

The parameters of Table 2 were used to tune the PID controller using the IMC technique. For comparison purposes, an attempt was also made to tune the controller using the Ziegler-Nichols method. However, it was found that the ultimate gain needed for achieving a state of marginal stability would lead to temperatures that exceeded by far the diode's temperature operating range. Therefore, it was not possible to use the Ziegler-Nichols method in this case.

In order to test the effectiveness of the IMC tuning technique, two experiments were conducted. The first experiment involved a set-point tracking case, where the reference temperature was changed from 24°C to 30°C and the PID was asked to accurately track the new reference value. The temperature response, together with the set-point value and the maximum and minimum allowed temperature limits are shown in Figure 8. It can be seen that the PID controller manages to reach the reference temperature with a zero steady-state offset. This is the result of the integral action offered by the term (I), which guarantees that a steady state can be reached only at the reference value. It should also be noted that the PID controller manages to reduce the settling time almost in half, compared to the open loop response. Finally the closed loop systems exhibit a slightly oscillatory response without an overshoot of 25%.

The second experiment involved a disturbance rejection problem. In this case, the reference temperature was kept steady at 30°C. After the system reached steady-state operation at the desired temperature, an unknown disturbance was introduced, by constantly cooling the diode with a ventilator. The ventilation caused the diode temperature to drop and the PID controller was asked to return the temperature to the reference value. The temperature response, together with the set-point value and the maximum and minimum allowed temperature limits are shown in Figure 9. It can be seen that the PID controller manages to cancel the destabilizing effect of the ventilation and successfully bring the system back to the reference value. It should be noted that without the use of PID control the ventilation could cause the diode temperature to drop more than 10°C. The selected value of the IMC tuning parameter  $\tau_c$  was found to play an important role in the temperature response. Higher values of  $\tau_c$  gave rise to a more oscillatory behavior, whereas lower values eliminated oscillations, but resulted in more sluggish responses.

Table 1 Tuning parameters for the Ziegler-Nichols and the IMC methods

PID term	Ziegler-Nichols	IMC
Proportional	$K_c = 0.6K_u$	$K_c = \frac{1}{K} \frac{\tau_1}{\tau_c + \theta}$
Integral	$\tau_I = P_u/2$	$\tau_I = \min[\tau_1, 4(\tau_c + \theta)]$
Derivative	$\tau_D = P_u/8$	$\tau_D = \tau_2$

As the main objective of the temperature control scheme for this particular application was to keep the temperature at a specific reference value at the presence of unknown disturbances, the focus was given on the disturbance

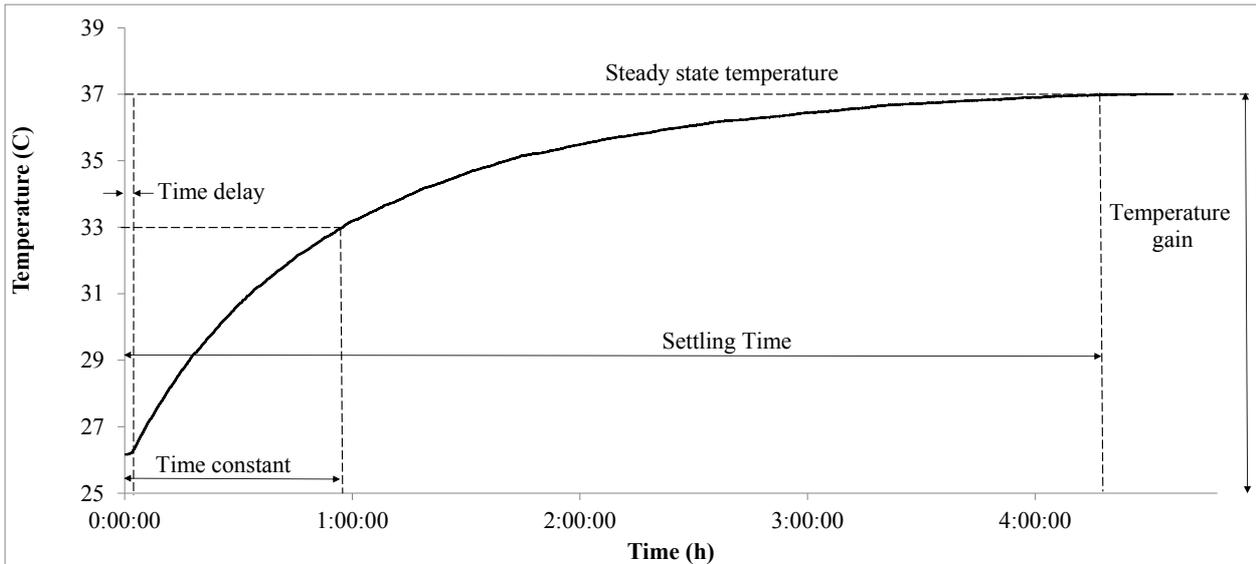


Fig. 7 Open loop response to a step change to the PWM from 0% to 16%

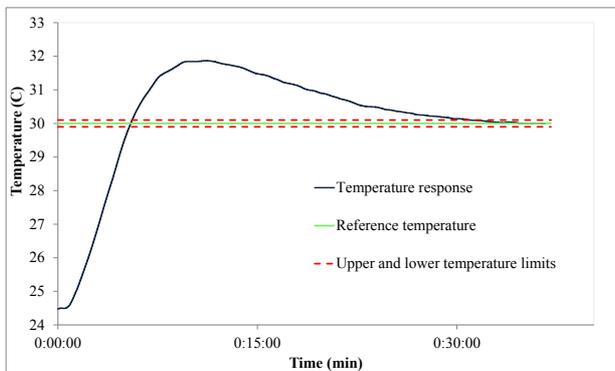


Fig. 8 Temperature response for the set-point tracking problem

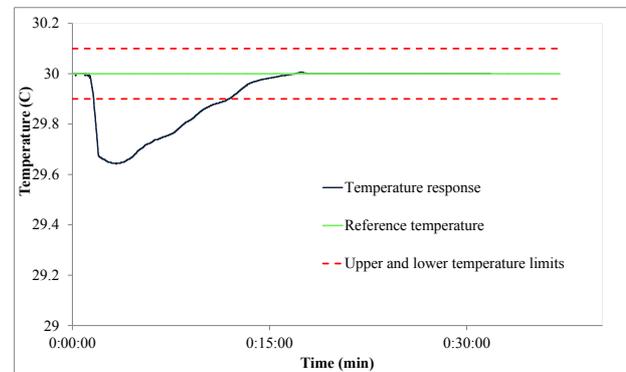


Fig. 9 Temperature response for the disturbance rejection problem

rejection case. For this reason a value of  $\tau_c = 0.35$  was selected, guaranteeing fast rejection of the introduced disturbance, albeit at the cost of slight oscillations in the set-point tracking problem.

**Table 2.** Transfer function parameters identified based on the open loop response

Parameter	Symbol	Value
System gain	$K$	0.001
Dominant time constant	$\tau_1$	57 min
Time delay	$\theta$	1 min
Second order time delay	$\tau_2$	4 min

## 5. Conclusions

In this work we present the development of a prototype microwave radiometer used to form a thermal image from

the tissues of the human body for medical reasons. A critical point in the radiometer operation is thermal stabilization of the NC303 noise diode, used for delivering symmetrical white Gaussian noise. This is achieved by designing a closed loop control scheme based on a PID controller. The IMC method is chosen for tuning the controller, as it provides good performance; the Ziegler-Nichols method on the other hand was found to be inapplicable for this particular problem. The proposed control scheme was tested on two different problems, namely set-point tracking and disturbance rejection. Satisfactory temperature responses were obtained for both problems but more emphasis was given in tuning the controller for disturbance rejection, which is more essential for this particular application. Future research involves coupling the PID controller with a thermoelectric cooler based on the Peltier effect, in order to maximize the benefits derived from PID control.

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