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HEADSET BLUETOOTH AND CELL PHONE BASED CONTINUOUS CENTRAL BODY TEMPERATURE MEASUREMENT SYSTEM

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ABSTRACT

The accurate measure of the central temperature is a very important physiologic indicator in several clinical applications, namely, in the characterization and diagnosis of sleep disorders. In this paper a simple system is described to continuously measure the body temperature at the ear. An electronic temperature sensor is coupled to the microphone of a common commercial auricular Bluetooth device that sends the temperature measurements to a mobile phone to which is paired. The measurements are stored at the mobile phone and periodically sent to a medical facility by email or SMS (short messaging service).

***Index Terms*—** Sleep Disorders, Acquisition Device, Mobile phone, Kalman

1. Introduction

The accurate measure of the central temperature of the body is a physiologic indicator very important in several clinical applications, namely, in the characterization and diagnosis of human sleep disorders to estimate the circadian rhythm of the patient which is roughly a 24-hour cycle in biochemical, physiological or behavioral terms [1]. The classic phase markers for measuring the timing of a mammal's circadian rhythm are melatonin secretion and body temperature. Direct measurements of *melatonin* secretion is difficult and is only possible in laboratory or medical facilities. The most used method to indirect estimate the circadian rhythm of *melatonin* secretion is the central body temperature[2] because both cycles are synchronized, as shown in Fig.1, and measure temperature is easier.

Traditionally, body temperature has been measured by contact thermometers in the oral, rectal or axillary sites. These locations are choices of convenience rather than correctness, because they do not accurately reflect the internal (core) body temperature [3]. The most common and accurate thermometers commercially available are not suitable to continuously monitor the temperature because they need human intervention. Several sophisticated solutions have been proposed such as the patent [4] where a capsule with a temperature sensor is ingested or inserted in the rectum or the patent [5] where a dedicated Bluetooth earphone device is used to send the *tympanic* temperature to a fixed computer.

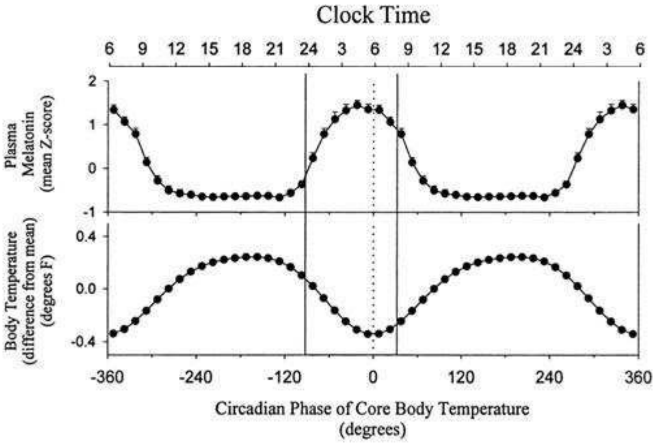

Fig. 1. Daily *melaton*in cycle production ad the tempseraure cycle.

Fig. 2. Auricular Bluetooth.

In [6] a system based on a cell phone is used to achieve the desired mobility. The authors propose a Bluetooth device to acquire several biomedical measures that are transmitted to the medical facility by the cell phone network. However, the proposed solution involves expensive acquisition dedicated hardware.

The solution proposed in this paper[1] aims at using the powerful and not expensive Bluetooth auricular devices and

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mobile phones, widespread around the world, to obtain a low cost, highly sophisticated and intelligent thermometer to continuously measure the central temperature of the body at the ear (*tympanic* membrane). The system uses a commercial auricular Bluetooth coupled to a simple and small electronic temperature sensor, as shown in Fig. 2.

The system, schematically represented in Fig.3, is based on a mobile phone paired with a Bluetooth auricular device that continuously send the measured temperature at the inner ear, strongly correlated with the tympanic membrane temperature, to the mobile phone. The stored data at the mobile phone may be periodically sent by email or SMS (short messaging service) to a medical facility for control purposes.

The software running at the mobile phone adaptively inquires the auricular Bluetooth to reduce the auricular consumption and extend the system operation time and filters the data.

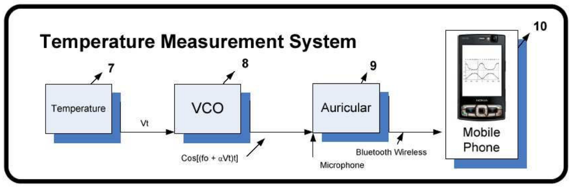


Fig. 3. Schematic representation of the central temperature measurement system based on a headset Bluetooth paired with a cell phone.

2. System Description

The core of the system is an electronic temperature sensor coupled to a commercial auricular Bluetooth as displayed in Fig.2. The temperature information is sent to the mobile phone through the Bluetooth microphone channel by using a *pulse width modulation* (PWM) carrier with central frequency $f_0 = 2.5$kHz. The frequency shift is at maximum 200Hz in the expected range of temperatures, $|f - f_0| \leq 200$. At the mobile phone, a software decodes the signal, process, store and send it to a remote place.

The sensor circuit, powered by the auricular battery, is implemented in miniaturized *Surface Mount Device* (SMD) technology in order to accommodate the whole components near the microphone of the auricular Bluetooth and its consumption is about 3 mA which allows a continuous measuring in a 24 hour basis.

The electronic circuitry, represented in Fig.4 is based on the temperature sensor LM334 directly coupled to the *precision voltage-to-frequency converter* LM331. This frequency encoder generates the PWM carrier that is injected in the audio channel through a capacitor to isolate both circuits from a DC point of view. The temperature sensor is highly linear in a wide range of temperatures.

The software running at the mobile phone is developed in Phyton and performs the following operations: i) adaptively inquiring the auricular Bluetooth, approximately at each 30 seconds, to acquire two seconds of audio information containing the temperature data when no conversation is in course. This adaptively sampling strategy is used to optimize the energy consumption of the auricular and increase its operation time. In this strategy the sampling rate is adaptively estimated according the evolution of the temperature curve estimated up to the present instant, leading to a sampling rate increasing when the derivative of the signal increases and the sampling rate decreases in the slow changes regions, as it is described in the next section, ii) demodulate the audio signal and filter the temperature signal with a *Kalman* filter, iii) store at the memory card of the mobile phone the estimated value of temperature, iv) periodically send to a medical facility the log file containing the temperature values by *short message service* (SMS), email or Bluetooth to a laptop, v) generate alarms when the auricular charge is ending to be replaced by the other that was previously charged, vi) the program is also prepared to generate alarms in several situations such as high abnormal temperature, long periods with signal absence or non sense temperature values (incorrect position of the auricular), vii) implement high level signal processing of the temperature signal such as estimation and displaying of the circadian cycle of the temperature, its phase shift and distortion measures with respect to the normal shape and viii) in an alternative mode of operation the auricular Bluetooth may be inquired a single time in response of manual command of the user.

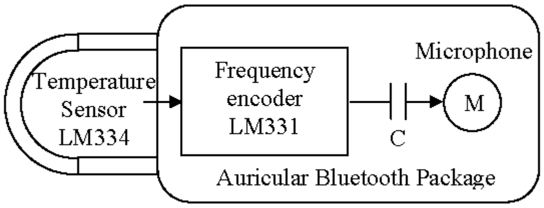


Fig. 4. Temperature sensor electronic circuit.

3. Adaptive sampling and demodulation

Each temperature sample is obtained from the frequency of a Δt seconds modulated audio wave carrier, modulated in PCM 16 bit, according with the following expression

$$T(t) = \beta f(t) + \gamma \tag{1}$$

where $f(t)$ is the instantaneous frequency at t instant and β and γ are constants computed in the calibration procedure. This calibration procedure is performed by emerging the sensor in melting ice and exposing it to steam of boiling water. The two obtained measured frequencies, f_0 and f_{100} are used to compute β and γ as follows

$$\begin{bmatrix} \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} f_0 & 1 \\ f_{100} & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 100 \end{bmatrix} \tag{2}$$

At each sampling slot $\Delta t = 2$ sec the temperature is assumed to be constant which is acceptable because the time constants associated to the temperature dynamics are usually much more larger than Δt. The frequency at each audio section is computed by counting the number of zero-crossing of the audio carrier at the corresponding section, N, according the following expression

$$f(t) = \frac{N}{2\Delta t} \text{ Hz} \tag{3}$$

where t is the central time instant of the section and Δt is the time length of the section.

The obtained sample is filtered by a Kalman filter adapted to deal with non uniform sampling. This procedure is performed in order to reduce the auricular battery consumption without degrading the estimated temperature signal. Here, the sampling instants are assumed to be a multiple of a minimum sampling period, Δt_s. The adaptive algorithm decides, at each sampling instant, if an acquisition is or not performed according to a criterion base on the previous acquisitions. Minimum and maximum values for the sampling time are assumed, Δt_m and Δt_M respectively and the sampling times are given by

$$t(n) = t(n-1) + \delta(n) \tag{4}$$

where $t(n)$ is the n^{th} sampling time and $\delta(n) = g(|dT(n)|)$ is the changing interval between two consecutive sampling times depending on the function $g(x)$ and on the estimated temperature derivative at the n^{th} instant, $dT(n)$. The scaled and shift sigmoid function $g(x)$, used to avoid abrupt changes on the inter sampling times, represented in Fig.5.a), is

$$g(x) = \Delta t_M - \frac{\Delta t_M - \Delta t_m}{1 + e^{-(x-\xi)}} \tag{5}$$

where $\xi = 1$ is a shift constant and the estimated derivative, represented in Fig.5.b), is computed as follows

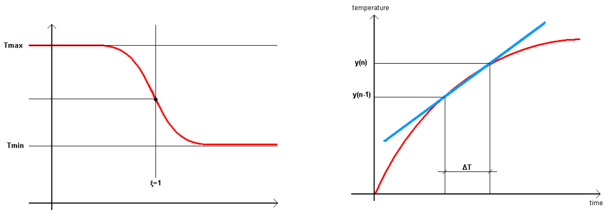
$$dT(n) = \frac{T(n-1) - T(n-2)}{t(n-1) - t(n-2)} \tag{6}$$

When the absolute derivative value of the estimated temperature curve $T(n)$ decreases the sampling rate approaches Δt_M and when increases the sampling rate approaches Δt_m.

The signal $T(n)$, acquired at instants $t(n)$, is noisy with a lot of outliers due the movements of the patients or unexpected displacements of the sensor from its regular position. The vector of sampling times may be

$$\mathbf{t} = \{0, 1, ..., N-1\}\Delta t_s \tag{7}$$
$$\mathbf{t} = \{k_0, k_1, ..., k_{L-1}\}\Delta t_s \tag{8}$$

for the uniform and adaptive sampling strategy respectively where $0 \leq L \leq N$ and $0 \leq k_0 \leq ... \leq k_{L-1} \leq N-1$.



(a) Sigmoid function. (b) Temperature derivative.

Fig. 5. Adpative sampling.

The Kalman filter [7], suitable to filter these data, aims at to recursively compute the *minimum square error* (MSE) state space unknown variable from the previous and present observations where the following 1D model is assumed [8]

$$T(n+1) = T(n) + q(n) \tag{9}$$
$$y(n) = T(n) + r(n) \tag{10}$$

where $y(n)$ are the noisy observations and $q(n) \sim \mathcal{N}(0, \sigma_q^2)$ and $r(n) \sim \mathcal{N}(0, \sigma_r^2)$ are normal distributed random variables with variances σ_q^2 and σ_r^2 respectively.

The estimated denosied signal is obtained from

$$\hat{T}(n) = \hat{T}^-(n) + K(n)\left[y(n) - c\hat{T}^-(n)\right] \tag{11}$$

where $\hat{T}^-(n)$ and $\hat{T}(n)$ are denominated *a priori* and *a posteriori* estimates of $T(n)$ respectively. $K(n)$ is the so called *Kalman gain* and $y(n) - c\hat{T}^-(n)$ is called *residue* or *innovation*. The *a priori* variable $\hat{T}^-(n)$ is the optimum estimates before the observation $y(n)$ is acquired. This estimate is updated with the *innovation* term multiplied by the *Kalman Gain*, $K(n)$, to produce the *a posteriori* estimate of $T(n)$, $\hat{T}(n)$. This is the optimum estimate of $T(n)$ given the present and all previous observations.

The filtering sequence is

$$\hat{T}^-(n) = \hat{T}(n-1) \tag{12}$$
$$P^-(n) = P(n-1) + \sigma_q^2 \tag{13}$$
$$K(n) = \frac{P^-(n)}{P^-(n) + \sigma_r^2} \tag{14}$$
$$\hat{T}(n) = \hat{T}^-(n) + w(n)K(n)\left[y(n) - T^-(n)\right] \tag{15}$$
$$P(n) = [1 - K(n)]P^-(n) \tag{16}$$

where

$$w(n) = \begin{cases} 1 & \text{if } y(n) \text{ was acquired} \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

The variable $w(n)$ controls the updating process when new data exist according with the sampling instants provided by (4). When no observations are acquired the output of the filter is the *a priori* estimate of $T(n)$, $T^-(n)$. The parameters σ_r and σ_q are used to tunned the algorithm and define the degree of smoothness of the solution.

The implementation of this *Kalman filter* is performed in Phyton and runs in real time at the mobile phone where the pair containing the sampling time and the respective estimated temperature, $[t(n), \hat{T}(n)]$, is stored at the memory card of the mobile phone in the log file.

4. Experimental results

In this section examples of application of the system are presented.

In the first example, the system placed on shadow and well-ventilated position, was used to acquire the air temperature of 24 hour period. The curve of temperatures are present in Fig.6a) and the corresponding curve of temperatures obtained by the Meteorological Institute of Lisbon, in a near location (20km) is displayed in Fig.6b). The similarity of both curves is clear.

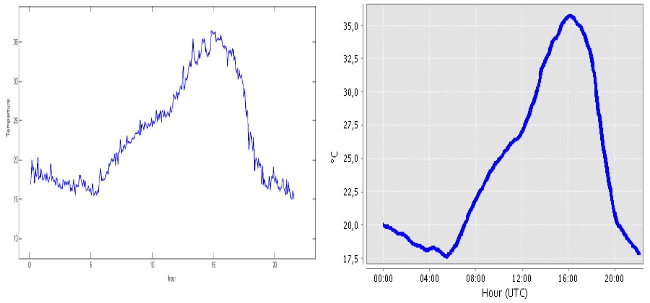


Fig. 6. Air temperature with the system proposed here (left) and from the meteorologic station in Lisbon (right).

The other test, with the *tympanic* temperature, was a 24 hour acquisition experiment and the results are shown in Fig.7. These results reveal the effectiveness of the filtering process and the ability of the system to track small temperature changes along the circadian cycle. These results, however, are displayed only to illustrate the operation of the device with real subjects. To possess a physiological meaning much more tests and controlled conditions are needed.

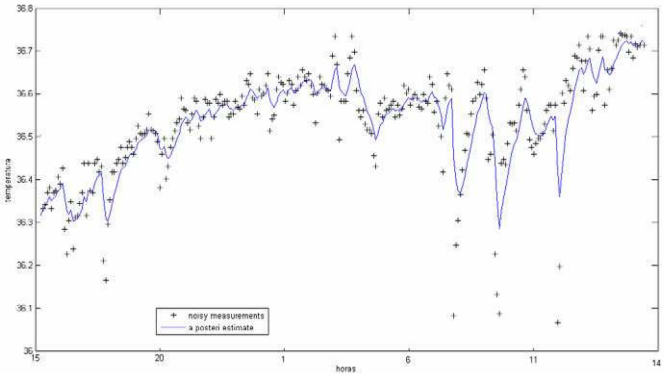


Fig. 7. Acquired data from the *tympanic* temperature (dots) and the corresponding filtered signal with the adaptive *Kalman* filter(line).

For the specific auricular Bluetooth used in this experiment, a common one, the maximum current consumption of the electronic thermometer was 3mA wich allowed to acquire approximately 500 samples which corresponds to approximately to 0.35 samples per minute or, equivalently, to a sample at each 3 minutes. This is however an average value. In fact, because the sampling is adaptive, when the temperatures decreases or increases fast the number of samples per minute can raise up to four.

5. Conclusions

In this paper a system to continuously measure the the central temperature of the body at the ear is described. The system is based on an auricular Bluetooth paired with a mobile phone. A simple hardware composed by a highly linear temperature sensor. The goal of this system is to measure, in a continuous and automatic basis, the *tympanic* temperature for sleep disorders diagnosis. The acquired data, stored and processed in the mobile phone, is used to compute relevant clinical indicators for the medical doctor, such as circadian phase shift or abnormal temperature circadian patterns. The raw data as well as the indicators are posteriorly sent to a medical facility by email or *short message service* (SMS).

The system was tested in real conditions with real patients and its usefulness from a clinical point of view was verified.

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