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Technical note

A comparative study for the development of a thermal odoscope for the wearable dynamic thermography monitoring

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We dedicate this paper to our friend Charly Maccioni

Abstract

Background:: The need of the reliable continuous monitoring of temperature is rising in many clinical applications. Today the use of thermography has become central for instance in the analysis of breast cancer, for the survey of inflammatory processes and certain skin areas during physical exercise. The core of the problem is the development of an ad hoc instrument, because traditional methodologies such as infrared and liquid crystals are no longer suitable.
Material and methods:: We developed a dedicated simulation set-up using Matlab R12 procedures (The Mathworks, USA) and P-spice models (Interlink, USA). We simulated the realisation and use of three different equipment configurations for thermography, one based on PTC sensors, another on thermocouples, a third one on specific integrated silicon components. We also bench tested one prototype.
Results:: The results showed the feasibility of the realisation of the instrument and the validity of the data obtained by means of the simulation.

Keywords: Simulation; Thermography; Odoscope

1. Introduction

1.1. The utility of thermography

Thermal imaging of the skin has been used for several decades for the monitoring of the temperature distribution of the human skin. Abnormalities such as malignancies, inflammation and infection cause localized increases in temperature, which shows as hot spots or as asymmetrical patterns in an infrared thermogram. Even though it is non-specific, thermography is a powerful detector of problems that affect the patient's physiology.

1.2. The use of thermography

One of the main areas where thermography has shown its potentiality is the breast cancer thermography as it is well documented by Miyauchi in his recent review [16]. Many authors focused on the breast cancer thermography and tested the method in sensitivity, validity, capacity in discriminating density and size of tumors, response to chemotherapic therapy and the dependence on the circadian rhythms. (*Sensitivity of the method*) Yokoe et al. [17] showed the role of cancer thermography for the detection of breast cancer and also tested the sensitivity and the specificity of this method. (*Validation of the method*) Yahara et al. [18] proposed a study for evaluating the validity of thermography in breast examination, he performed a contact thermography and measured the direct temperature by inserting a needle-type thermometer into the tissue; the core temperature of the tumor and the temperature of the tissue surrounding the tumor were compared with normal tissue, he also found a relationship between the surface temperature and the high-risk group of breast cancer and also found that abnormalities in temperature were reflected in thermography and that a higher surface temperature was related to the dissociated wide area of the thermogram. (*Density of tumor*) Haga et al. [20] showed the

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significance of the locoregional hyperthermic area observed by contact thermography in relation to the maximum density of tumor enhancement. (*Size of tumor*) Sterns et al. [21] showed that thermographic abnormality is associated with tumor size and lymphonode involvement; He also correlated the thermal abnormality and its relationship to survival. (*Chemiotherapic effect*) Kurihara et al. [22] examined temperature differences between a cancerous breast and its counterpart normal one by contact thermography before and after preoperative chemotherapy, and evaluated the relationship between the changes in the thermograms and response to chemotherapy in six patients with breast cancer. (*Differential analysis malignus/benignus*) Geshelin et al. [23] showed the utility of the contact thermography in the differential diagnosis of benign and malignus tumors of the breast. (*Importance of circadian events*) Keith in reference [19] showed that the thermal variations, which characterize the tissue metabolism in the breast cancer are circadian ("about 24 h") in periodicity.

Another important use of the thermography is in the thermal monitoring during the physical exercise.

Zontak et al. [14] for example explored the use of thermography during the physical exercise and noted by means of an infrared system that blood flows and temperature variations are normally correlated. Physiology provides an explanation for this; in fact, in the initial phase of the exercise the demand of blood flows causes a certain degree of skin constriction; then, when the body temperature rises, the thermal regulatory process becomes predominant and cause the dilatation of skin blood vessels, which makes both the blood flow and heat conduction of the skin increase as showed by Johnson in reference [15]; however many of the pathologies described above could affect this physiological process and the thermograms could appear with abnormal patterns.

1.3. Why there is the need of a wearable device?

Even if the interest in the non-invasive multiple-parameter portable/wearable monitoring is rising as it is amply documented by Bonato in reference [13], the use of the non-invasive thermographical portable/wearable monitoring did not show to have a large diffusion and up to now in the above listed references it was limited only to wearable single thermometers as in many above described applications or multiple thermometers as in reference [6] and not for an area monitoring and not for the long time acquisitions. A wearable device could be easily ported and used in the above described applications for the long time-non invasive monitoring of the thermal activity for checking the presence of thermal abnormal patterns just like the Holter for the cardiograms and could be for example used in conjunction with other instrument for the movement analysis in clinics [24] or for completing the diagnosis of breast cancer which needs even long time acquisitions correlated to the circadian rhythms.

Another advantage of the wearable device is the price, in fact the three technologies reported above are low cost technologies especially if compared with the infrared ones.

1.4. The commonly used technologies for thermography

The transfer of the military technology for medical use has prompted this reappraisal of infrared thermology in medicine. Diakides in reference [3] showed as the technology developed for many years for the electronic war could be converted in medical technologies [4,5]. Jones in references [1,2] showed that digital infrared cameras have much improved spatial and thermal resolutions, and libraries of image processing routines are available to analyse images captured both statically and dynamically; he also showed that if thermographs are captured under controlled conditions, they may be readily interpreted for diagnosing certain conditions and for monitoring the reaction of a patient's physiology to stresses. Another commonly used technology is based on liquid crystals, which change their colours in accordance to two or three thresholds.

1.5. The technologies suitable for the wearable thermography

The most commonly used technologies for thermography are not applicable for the continuous wearable monitoring; in fact infrared thermography needs the use of digital cameras which are not easily wearable; on the other hand the use of liquid crystals is not feasible, in fact they permit the detection of two or three thermal ranges according to prefixed thresholds and are not easily wearable.

There are three approaches that can be followed for implementing wearable sensors for thermography based on the use of the following components:

- *Thermistors*, preferably with the positive thermal coefficient or negative thermal coefficient for the high resolution they furnish.
  Bolton [6] developed a compact data logger for ambulatory skin temperature measurement with which he achieved an eight-channel, high-resolution temperature-monitoring system based on thermistors.
- *Silicon integrated components*, which found several applications in the 1980s [7–9], but the advances in microprocessor technology and the package reduction now permit performances that were previously unthinkable.
- *Thermocouples*, Bolton et al. [6] showed that technologies based on thermocouples had the limitation of needing cold junction compensation.

1.6. The aim of the paper

We afforded the problem of the set-up of a simulation environment for performing a comparative study for the development of a device for the wearable dynamic thermography monitoring. Our principal aim was then to develop an environment for the simulation and to extend this to all of the there different technologies described above with particular reference to the performances of the device such as the thermal and spatial resolution, the stability and the encumbrance.

In order to improve the simulation data confidence we compared the better-simulated solution to the experimental data.

2. Materials and methods

2.1. Why these experiments

The purpose of the paper was to explore different solutions suitable to develop a wearable device. Particular attention was devoted to the performance of the instrumentation such as the thermal and spatial resolution. Considering that the device should be wearable and permitting long time acquisition particular attention was also devoted to the study of the encumbrance by varying the number of sensors and to the stability by varying the temperature input.

In order to perform this objective firstly we realized a simulation environment with the circuital and sensor models, secondly we used the environment for obtaining the performances of the device, such as the spatial and the thermal resolution and the stability of the response by varying the temperature; in order to test the level of confidence of the circuit models we also implemented the best simulated solutions.

2.2. The realization of the simulation environment

The realization of instrumentation now can be quite precisely simulated before its realization, by means of well to adherent the reality models. This can be achieved by means of the computer-aided equipment (CAE)–computer aided design (CAD)–computer aided manufacturing (CAM) tools. Manufactures furnish application software which comprehends tools for the simulation of the circuital response, for the estimation of layout occupancy and encumbrance; these are currently used by mechatronics manufactures and their precision was tested in the last two decades from the application specific circuits (ASIC) realized by means of the very large scale integration to the realization of large boards [25–27]. However the simulation model of the sensors furnished by the manufacturer was not suitable for this specific application where the central parameter is the temperature. This exactly appears in this application where simulation models should respond not only to electric variation but also to thermal variations. This is relevant for the thermal sensors used in the device. We afforded then the problem of integrating to a CAE–CAD–CAM tool the simulation model of the thermal sensors developed to study the sensitivity of the components to different thermal variations.

The wearable device comprehends the sensor unit (odoscope unit) with the thermal sensors; the service unit which comprehends the sensor polarization circuitry and the amplification and conditioning circuitry. The sensor unit may be realized by means of three different sensors: thermistors, thermocouples, integrated sensors; the polarization circuitry is different depending on the sensor used; the amplification and conditioning unit is standard with the values of resistance and capacitance chosen to optimize the circuital response. We realized the sensor models by means of the Simulink tool of Matlab R12 (The Mathworks, USA) according to the datasheets of the components. The rest of circuitry was modeled by means of the P-spice (P-Spice, USA) models for the performance simulation and Protel (Protel, USA) for the schematic entry and placement and routing for the layout estimation.

We then simulated the three different solutions.

The first solution was based on commercial thermistors with positive thermal coefficient.

For the simulation model we used the following relationship to describe the temperature dependence.

$$R_{T2} = R_{T1}\,\mathrm{e}^{B(1/T1-1/T2)} \qquad (1)$$

and used the N-silicium semiconductor silicium, in fact it has a better linear response in the thermal range of interest, for the realization of the model by means of the package Simulink (Matlab R12, USA) we made reference to the thermistor used by Bolton in references [6,10].

The second solution is based on the use of integrated. For the realization of the model we made reference to the lm335 by National Semiconductor [6,12].

The third solution is based on thermocouples with a polarisation circuit for cold junction compensation, based on the Seebeck effect. The relationship between temperature and voltage is the following:

$$V = A\,\Delta T + 0.5B\,\Delta T^2 + 0.33C\,\Delta T^3 \qquad (2)$$

For the realization of the model by means of the package Simulink (Matalab R12, USA) we made reference to the encumbrance of the thermocouples used for the thermal measurement systems such as multimeter fluke 179EGFID [11]. The polarization circuits were those indicated by the manufacturers' applications [12,28]. We preliminary tested the simulation model by comparing the simulation results to the experimental data obtained with different thermocouples (iron–costantana, copper–constantana, chromel–alumen, chromel–constantana) [29,30] reported in Table 5 in the thermal range of interest of human temperature (25–41 °C) showing a distance between the two methods never higher than 1×10^{-2} °C. We also decided to use a model based on the chrome–aluminum thermocouple because it is more sensitive to little thermal variations in the range of interest.

The packages used were those chosen in order to minimise the layout occupancy.

The amplification and conditioning circuit comprised also the analog multiplexes (to select the different channels); the conditioning circuit was composed by a non-inverting operational amplifier plus a Sallen & Key filter.

2.2.1. Description of the simulation process

The core of the environment was developed by means of the Matalab R12 tool box (The Mathworks, USA). We basically used The Simulink tool box for the realization of the models of the sensors also using the datasheets properties and some bench tests results performed by means of a controlled oven for determining the statistical parameters. Each sensor model was structured as a procedure Pk(S,I) with a state depending on the input history, which restitutes simulation P-Spice parameters to a P-Spice modelisation of the conditioning chain (Interlink, USA) simulation. In order to perform and solve complex differentiations we also used the ordinary differential equation system solver (ODE). The function quadl() we used for the integrations was based on the adaptative Lobatto quadrature algorithm, with absolute tolerance error in the integral set to 10^{-7}. The inputs to the simulation environment describing thermal variations were modeled as processes by means of the basic matlab functions of the matlab Statistics toolbox, which permits a process modeling by means of functions with imposed statistics (distribution, mean value variance).

Fig. 5 illustrates a flow chart describing the process, which for clearness reasons was organized in three layers:

(1) the input layer;
(2) the sensor layer;
(3) the P-spice layer.

2.3. The simulation run

2.3.1. Area estimation parameters

The area estimation of the two units gives an idea of the encumbrance of the wearable unit as function of the number of sensors.

This parameter estimation was performed by means of the Automatic Placement and Routing of the Protel package. By means of this simulation run it is also possible to obtain the spatial resolution by estimating the distance among the sensors of the odoscope unit.

2.3.2. Static performances

The static thermal resolution resolution, accuracy, linearity and hysteresis were determined by simulating the assessment of different fixed temperature in the range (25–41 °C). The temperature was varied in the range by means of steps of 0.02 °C comparable with the accuracy of a mercury thermometer. This run was also used to obtain the calibration curves useful for the rest of the simulation and to optimize the values of the components of the service unit.

2.3.3. Dynamic stability

To investigate the stability of the thermal measurements over the long time measure there is the necessity of the use of suitable curves in the simulation with the thermal variation versus time; the problem is that these curves should be reproducible in practice and cover the physical phenomena

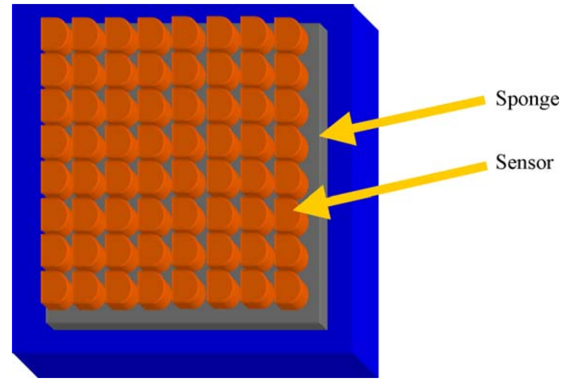

Fig. 1. Representation of the odoscope unit with the case.

of interest in the human skin variation. The first problem can be easily solved using a dedicated warming unit and recording the thermal variation as function of time, which can be furnished to the simulation. The second problem is quite difficult because the human skin thermal variation is application dependent. Our choice was to use one increasing and one decreasing thermal curve, which can be obtained by means of a warming test unit. These thermal laws have the gradient and the noise higher than those which can be obtained in the applications of interest [16], furthermore the temporal scale was chosen in accordance with the duration of physical exercise tasks [14].

$$T(t) = 25\,^{\circ}\mathrm{C} + 0.007t + n(t)(0 < t < 1800\,\mathrm{s}) \tag{3}$$

$$T(t) = 41\,^{\circ}\mathrm{C} - 0007t + n(t)\ (0 < t < 1800\,\mathrm{s}) \tag{4}$$

$n(t)$ is a random noise with mean value equal to 0.01 °C

2.4. The realization of the wearable and bench test unit

We realized the bench test unit used for obtain the curves and for testing the prototypes.

We also realized the prototype with 64 sensors of the silicon based solution and tested it in spatial resolution, area occupacy in thermal performances by means of a controlled oven and in stability by means of the warming test unit. Fig. 1 shows the picture representation of the odoscope.

3. Results

3.1. Simulation results

3.1.1. Area estimation parameters

The study of the area occupancy was performed varying the number of sensors with the low $N_s = 2^b$ with $4 \le b \le 8$. The pixel spatial resolution obtained with the odoscope is 12.5 mm^2 by means the thermocouples and 16 mm^2 by means the thermistors and the lm335 silicon integrated components. This spatial resolution remains constant by varying b and then the field of view.

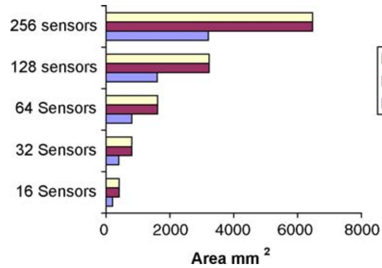

Fig. 2. Odoscope unit area estimation.

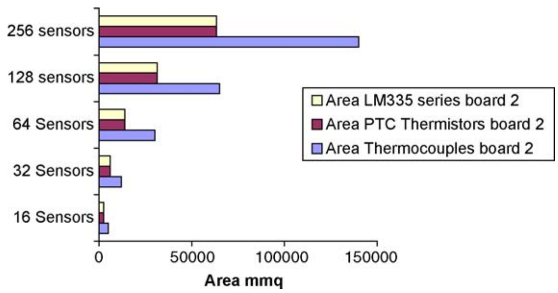

Fig. 3. Service Unit area estimation.

Table 1
Cut off frequencies and gain (simulated)

Sensor	Cut-off frequency Low-pass filter (Hz)	Gain
Thermocouples	600	84
PTC	720	84
Silicon component	624	84

Fig. 2 shows the changing of the layout encumbrance for the odoscope unit by varying the number of sensors.

Thermocouples showed a lower area encumbrance for this unit in the order of 50% of the other two solutions; this ratio remains constant by increasing the number of the sensors.

Fig. 3 shows the layout encumbrance for the board of the service unit by varying the number of sensors. Thermocouples showed a higher area encumbrance for this unit in the order of 200% of the other two solutions; this ratio remains constant by increasing the sensor number of sensors.

3.1.2. Static performances

Table 1 shows the static performances (resolution, accuracy, linearity, hystresis) obtained thanks to the simulations. At this step it was also possible to obtain the calibration curves and the parameters of the amplifier and the Sallen & Key low pass filter, Table 2 shows these values.

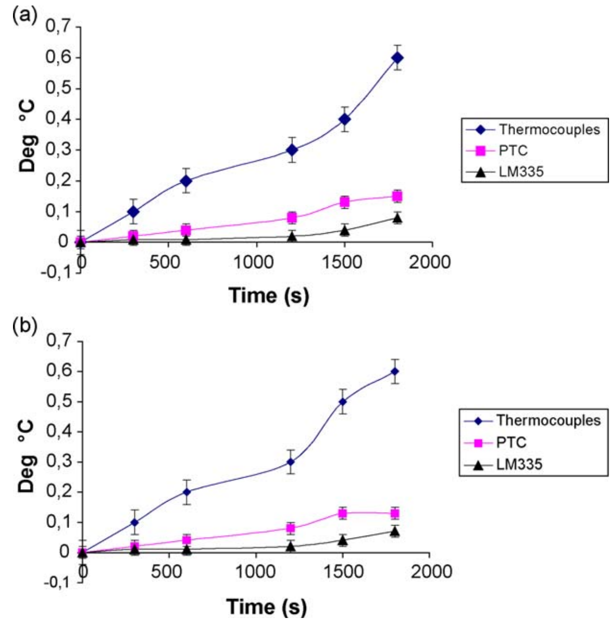

Fig. 4. (a) Mean and standard deviation error to the input of Eq. (3), (b) mean and standard deviation error to the input of Eq. (4).

3.1.3. Dynamically stability

Fig. 4a and b shows the mean simulated error with the standard deviation of the mean obtained by means of the two selected inputs (Fig. 5).

3.2. The realization of the testing unit

The testing unit comprehended a *w*arming *t*est unit realised in our lab and a commercial controlled oven. The WTU was realised by means of a conductive-gum disk and two electrodes with an adiabatic case, with current injection controlled by a PIC16F87 (Microchip, USA) and a mercury thermometer with 0.02 °C of accuracy, the PIC was used to pilot the current injection to obtain the curves reported above.

3.3. The realization of the wearable

Fig. 1 shows a picture of the odoscope with the transpirant sponge necessary in biomedical sensor contact monitoring and with the assembly of the sensors. The layout area was 1616 mm^2 for the odoscope unit and 10,020 mm^2 for the service unit. The weight of the equipment was 215 g for the odoscope unit and 647 g for the service unit. The component part list comprehends the following optimized packages: To92 for the thermal sensors, Dual in Line 16 pin package for the IC Amplifiers, Dual in Line 28 pin package for the analog

Table 2
Static response of the three sensor chains (simulated)

Sensor	Cross-talk	Non-liniearities (%fs)	Hysteresis (%fs)	Accuracy (%fs)	Overall resolution in the range of interest
Thermocouples	None	±0.2	<0.2	0.5	>0.05
PTC	None	±0.1	<0.1	0.3	>0.1
Silicon component	None	±0.1	<0.1	0.3	>0.05

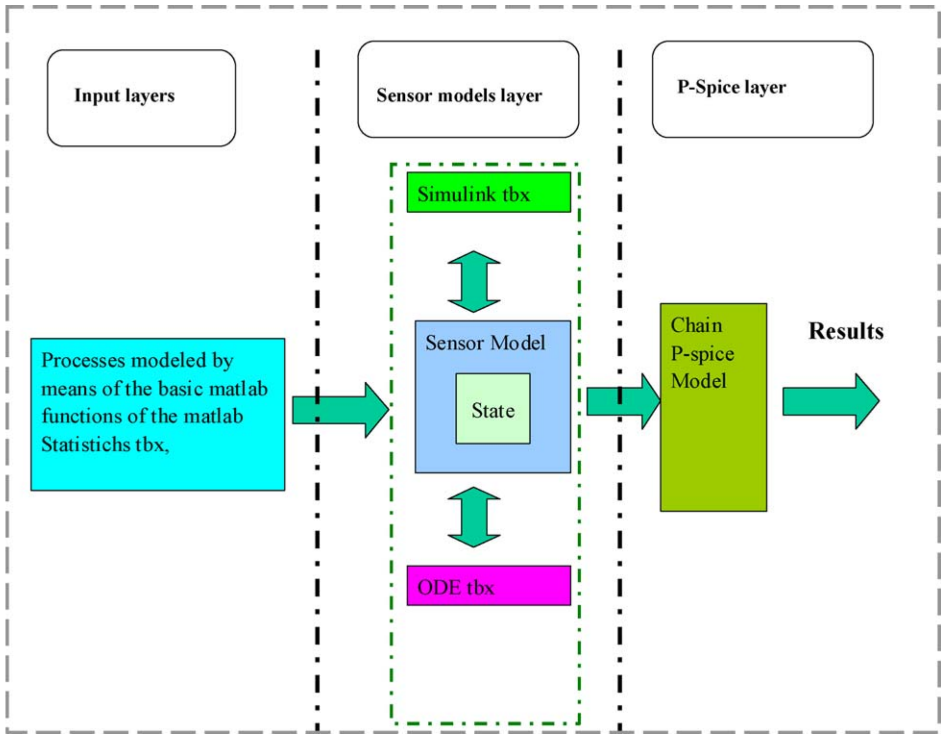

Fig. 5. Block diagram simulation environment.

multiplex and, Mrs25 package for the resistance, plus mica-silver radial condensers for high stability and performance.

The spatial resolution of the instrument was $1.6\,\mathrm{m}^2 \times 10^{-5}$ for a field of view of $1\,\mathrm{m}^2 \times 10^{-3}$.

3.4. Bench test results and comparison with the simulation results

3.4.1. Area and spatial resolution and static performances

The area encumbrance and the spatial resolution is in perfect accordance with the CAE–CAD–CAM placement and routing prevision just like the static performances as shown in Table 3.

3.4.2. Dynamic performances

The bench test obtained by means of the WTU gave rise to the maximal error differences between the simulated and bench-tested trials shown in Table 4 considering the two dynamic inputs.

Table 3
Static performances of the realised system

Cross-talk	Absent
Non-linearities (%fs)	±0.11
Hysterisis (%fs)	0.08
Accuracy (%fs)	0.29
Overall resolution in the range of interest	0.03
Layout odoscope unit (mm^2)	1616
Layout service unit (mm^2)	10020

Table 4
Maximum error difference

Eq. (3)	Eq. (4)
0.06	0.06

4. Discussion and conclusions

In this paper we showed the feasibility of the contemporary simulation of thermal and electrical parameters by means of the integration of models developed by means of the tool Simulink and P-Spice. The well-proved precision of the CAE–CAD–CAM systems permits also to exactly have a cost and weight preview of the simulated equipment. We have shown the scientific evidence emerging from the simulation analysis of three different devices for thermographical monitoring. In the specific, these are the rising considerations.

4.1. Area encumbrance and spatial resolution by varying the sensor numbers

4.1.1. Odoscope unit

The more optimized layout was obtained with the thermocouples. The layout obtained by means of the thermistors and the silicon sensors had the same degree of complexity. As for thermocouples, it should be borne in mind that the higher the frequencies, the more the isolation needed, which may enlarge the occupancy area up to 60%, losing the advantages with respect to the other sensors.

4.1.2. Service unit

The more optimized layout was obtained with the thermistors and the silicon components.

With the thermocouples, the need for cold junction compensation incremented the area and yielded the least optimized board.

4.2. Static performances

The simulation showed the lesser accuracy of the thermistor due to residual non-linearities and hysteresis that the calibration could not completely correct.

The thermocouples and the silicon components had a similar accuracy.

4.3. Dynamic peformances

In all of the simulation cases the silicon components followed the input better. The thermocouples showed the highest error due to their intrinsic slowness in following rapid thermal variations and then for this reason should be withdrawn for the long time monitoring. The thermistors showed intermediate performances. If we consider the maintenance versus time, other type of problems would arise, for instance, thermocouples oxidise in time, which would impair their performance.

All these considerations suggest that the silicon component chain is the choice technology for implementing an acquisition chain for clinical applications. Even though these components were originally intended for other applications, they feature interesting properties in the windows of interest, i.e., accuracy and stability.

4.4. Consideration on the prototype test

The bench test conducted on the silicon-component based realisation showed that simulated data and experimental data were in perfect accordance.

4.5. Limits of the contact technologies and possible solutions

As it is well known contact thermography suffers of the typical problems of the skin contact thermal measurement; an example of this is the commonly used thermography based on liquid crystals; it is based on large foils put into contact to the skin which from one side hamper the measure by means of the foils-to-skin interface, from the other side permit a very poor resolution, in fact they change the colours according to only two and three thresholds. By means of our simulated devices we have wearable solutions with high resolution and minimal encumbrance but we also have to account this limit, in fact attaching the sensor affects the heat distribution of the skin surface.

The sweating should be also avoided; in telethermography it affects the measure because the IR system detects the sweating vapour/water IR spectrum; in contact thermography the sweating should be avoided because it could cause the temperature drop. In order to minimise this problems we afforded the study of solutions based on peculiar sponges on the odoscope; these sponges are based on open cellular materials [30] used also for the development of sub-water dresses and facial prosthesis for burned patients which permit to respect also the following further aspects:

(1) the thermal exchange between the skin and the external environment should not be hampered;
(2) the gas/vapour exchange also should not be hampered because it could cause a thermal dropping;
(3) the material should be unallergical;
(4) minimisation of the conductance from the skin surface to the odoscope and vice versa;
(5) the material should be easily modelled.

4.6. The extension of the analysis to the clinical applications

After the realisation and the engineering of the prototypal the device will be fully used in clinical applications. Many are the clinical applications where the device could be used with success: neurology, vascular disorders, inflammation, rheumatic disorders, blood circulation, oncology, dermatological disorders, ophthalmology, surgery, neonatal on the study of the correlation of physical exercise and thermal variations and this not an exhaustive list.

A valid aid for the analysis could come from the development of heat-transferring-models specific for the application. Literature in fact is continuously showing the diffusion of more and more well-to-the-reality-adherent-models developed by means of Bio-heat-equations; the one developed by Suktanskii and Yablonsky for example in reference [31] was focused on an analytical model of temperature regulation in human head; as another example Stanczyk and Telega in their review focused on bio-heat equations on orthopaedics [32]. Furthermore, these equations could be conveniently solved by means of the ODE tool of Matlab previously described.

This means that the medical knowledge should be built by means of a process which is dynamically developed by means of the medical thermal acquisitions conducted from the physicians, the developing of suitable models based on the bio-heat equations developed by biomedical engineers and a comparison between the experimental results and the expected results from the models for the research of abnormal thermal patterns (see Fig. 6).

4.7. Future miniaturisation aspects

All of the technology used in the simulation or in the prototype is low cost if compared to the infrared one. This paper was developed to pave the way to hardware implementations of different technologies for thermographic wearable monitoring. The realisation of thermal odoscopes was investigated

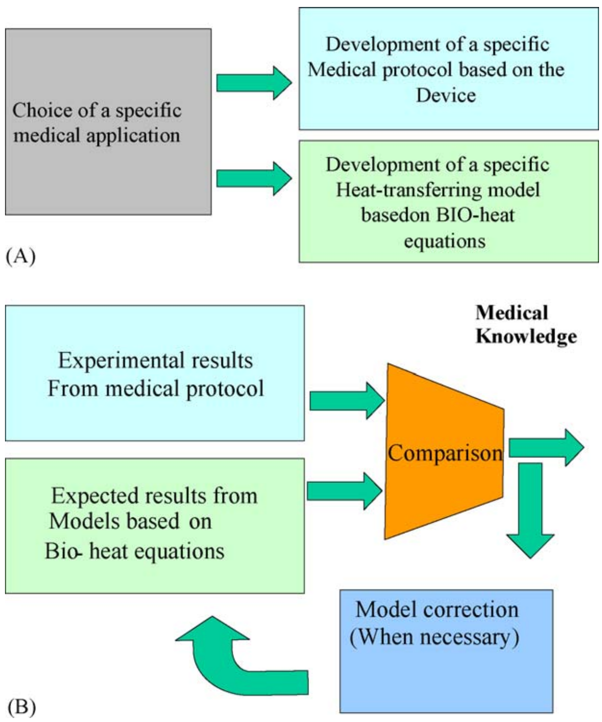

Fig. 6. (A and B) Flow-chart: the development of medical knowledge based both on the wearable thermal device and on the bio-heat equations.

Table 5
Different simulated thermocouples

Thermocouple	Code	Resolution (°C)
Iron–costantana	J	0.02
Copper–constantana	T	0.03
Chromel–alumen	K	0.01
Chromel–constantana	E	0.03

using commercial components with standard mounting packages. To reduce the area encumbrance the surface mounting technology or the hybrid technology realisation could be used but at the moment only few components are suitable in this technology (Table 5).

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