Using lock-in infrared thermography for the visualization of the hand vascular tree

Nabila Bouzida[1*], Abdel Hakim Bendada[1], Jean-Marc Piau[1], Moulay Akhloufi[1], Xavier Maldague[1], Mathieu Raymond[1]

[1]Computer Vision and Systems Laboratory,
Laval University, Quebec City (Quebec) G1V 0A6, Canada.
{jmpiau, bendada, maldagx, makhloufi}@gel.ulaval.ca

ABSTRACT

An imaging technique of the hand vein tree is presented in this paper. Using the natural human circulatory system and a controlled armband pressure around the arm, a lock-in thermography technique with an internal excitation is carried out. Since the stimulation frequency is inversely proportional to the inspection depth, the subcutaneous layer requires the use of a very slow frequency. Thus, a sawtooth waveform is preferred to minimize the duration of the pressure applied to the armband during the experiment. A frequency of approximately 0.03 Hz and a pressure range between 100 and 140 mmHg, according to the diastolic and systolic blood pressure, are used as stimulation. Then, dorsal hand amplitude and phase images are obtained with IR_view (Klein, 1999), a tool specifically designed to analyze infrared images.

The hand vein structure is thermally mapped by an infrared camera operating in the middle wavelength infrared range (MWIR) at room temperature. Parasitic frequencies are avoided by keeping the hand fixed. The resulting images show a gradient of temperature between surrounding tissues and the back-of-hand veins. The vascular signature segmentation is extracted from the amplitude and phase images by using a Fast Fourier Transform image processing technique. This work could be used for vein localization for perfusion or for the early diagnosis of vein diseases such as primitive varicose and deep vein thrombosis (DVT). A hand vein signature database for identification purposes is also possible.

Keywords: lock-in thermography, infrared vision, medical imaging, hand vein signature.

1. INTRODUCTION

The pathological and physiological states of the underlying tissues of the body could be revealed by the skin surface temperature. Heat is transmitted to the skin by the blood flow through the vessels, and from there by thermal conduction on the surface of the skin. The first step that a physician carries out in order to diagnose a patient is to measure the patient's temperature. The latter can be measured through contact, by a thermometer or a thermocouple, orally, rectally or by way of the external auditory canal. However, this contact affects the temperature of the observed system and is often concentrated on the local areas. The infrared camera however, is able to detect the natural thermal radiation of the body without any contact, and is also able to produce images representing the distribution of the temperature on various surfaces of the body. The use of infrared thermography [1] in medicine is then based on the natural thermal radiation of the skin.

In the last decade, interest in medical thermography has increased [2] following the great progress reached in processing software and the improvement in the speed and spatial resolution of infrared cameras. As stated before, the main advantage of this process is the contactless approach to diagnose the skin surface and the non-emission of harmful radiation as is the case when using the X-ray technique. With the exception of Doppler ultrasonography, other methods of imaging the vein-flow are invasive [3]. Indeed, infrared thermography uses only the natural radiation of the body. The human body emits infrared radiation principally between *(2- 20) μm* which is beyond the far infrared spectrum and has a

* Further author information:
N. Bouzida: E-mail: Nabila.bouzida.1@ulaval.ca ,

Thermosense XXX, edited by Vladimir P. Vavilov, Douglas D. Burleigh,
Proc. of SPIE Vol. 6939, 69390O, (2008)
0277-786X/08/$18 · doi: 10.1117/12.778680

peak between *(9 -10) µm* corresponding to about 310°K according to Planck's law of black-body radiation. The body emissivity is almost equal to 1. No correction for emissivity is then required.

Wu *et al*. [4] proposed a method of blood flow visualization in the forearm vessels using a modified version of lock-in thermography. What we are proposing, is an improvement of the method proposed by Wu, Busse and coworkers, with a detailed study and results, an image processing application for vascular extraction and also a suitable approach and tools for blood modulation. Our focus is only on the back-hand veins, not on the blood flow but rather on the thermal waves obtained on the vein surface and on the vascular structure identification.

The hand vein pattern is the network of blood vessels lying subcutaneously in the hand [7]. Recent work on vein visualization used near infrared (NIR) imaging and a lighting source composed of several LEDs to extract the vascular tree [5], [6]. No additional lighting source is used in our case. It is preferable to use a non-invasive material in the study of dorsal hand vein structure. Since the vein pattern is time-invariant, unique, different from a person to another, even from a right hand to a left hand of the same person, a typical application would be to build a database for human recognition or identification. Also, some research studies have used infrared thermography to help diagnose vein diseases such as Reynaud's phenomena, joint inflammation and venous thrombosis which is a blood clot that forms within a vein, changing its form.

2. BLOOD PRESSURE

Blood is carried from the heart to all parts of the body in arteries. The pressure in vessels varies in every cardiac cycle between a minimal value about 10 kPa (80 mm Hg) which called the Diastolic Pressure (DP), and a maximal value of about 16 kPa (120 mm Hg): the Systolic Pressure (SP) [9].

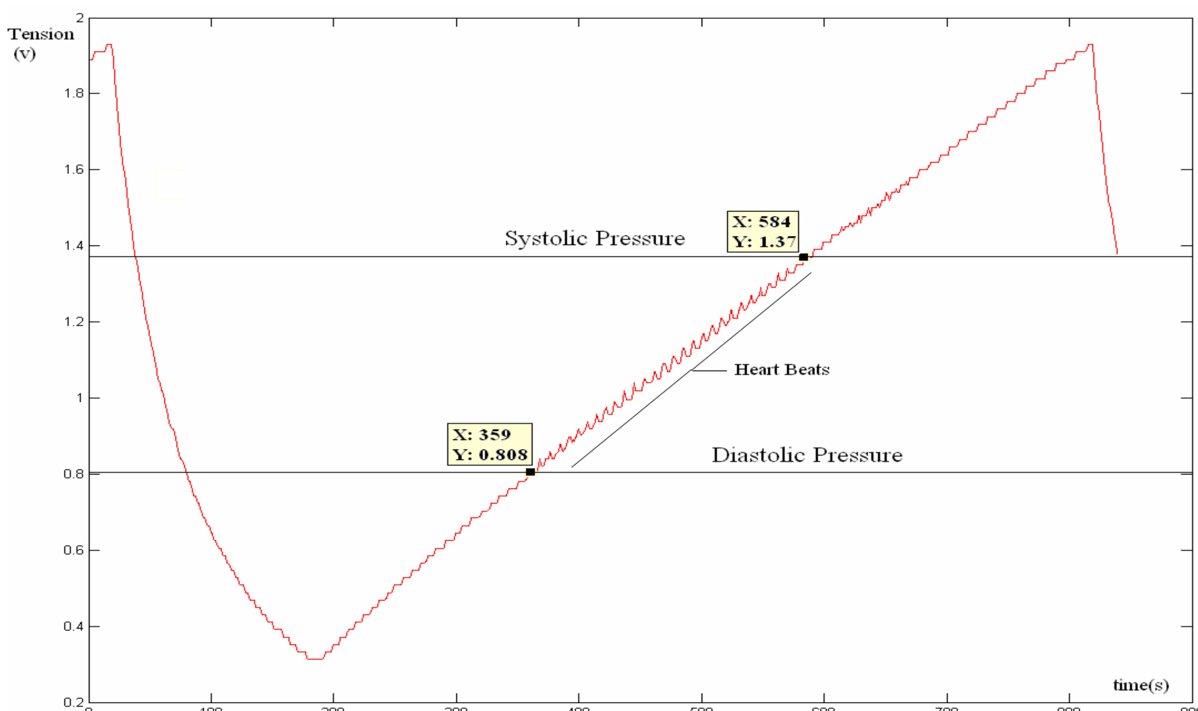


Figure 1 Heart beats noise between the Diastolic and Systolic values

The SP value is the maximum pressure that the blood exercises on the arterial walls when the heart is pumping the blood through the body, while the DP value is the lowest pressure in an artery between two heart beats. The blood pressure is obtained by placing an armband on the upper arm of a patient at rest and by auscultation over the brachial artery. The frequency of the arterial pressure wave is equivalent to the cardiac frequency which corresponds to 60-120 beats, thus equivalent to 1 to 2 Hz. In Figure 1, the applied pressure on the armband follows a command of 0.80 - 1.37 Volt which corresponds to 80-137 mmHg. As illustrated, the heart beat's noise is visible between the diastolic and systolic pressures of the person using this command.

3. EXPERIMENTAL SETUP

The proposed approach is processed in several steps as shown in Figure 2. An armband is placed on the person's arm to modulate the bloodstream. A system to command the applied pressure on the tensiometer armband is designed. A commercial blood pressure tensiometer has been modified for the purpose of the experiment. The controller commands the pressure through a pump. An analog signal of 1 Volt inflates the armband through the air tube until a pressure of 100 mmHg is reached. In the permanent state, the target will be equal to 1volt_DC. This control requires an input to which the output pressure will be adjusted. A periodic pressure is applied to the arm in order to induce an internal excitation which is transmitted through the bloodstream and through the arm to the hand vessels where it is detected by the infrared camera. An average pressure of about 80 mmHg is applied. An oscilloscope is used to select the stimulation wave and the frequency at which it is to be applied. The hand is kept steady on the table using 5 setting points to avoid movements causing an additional parasitic frequency.

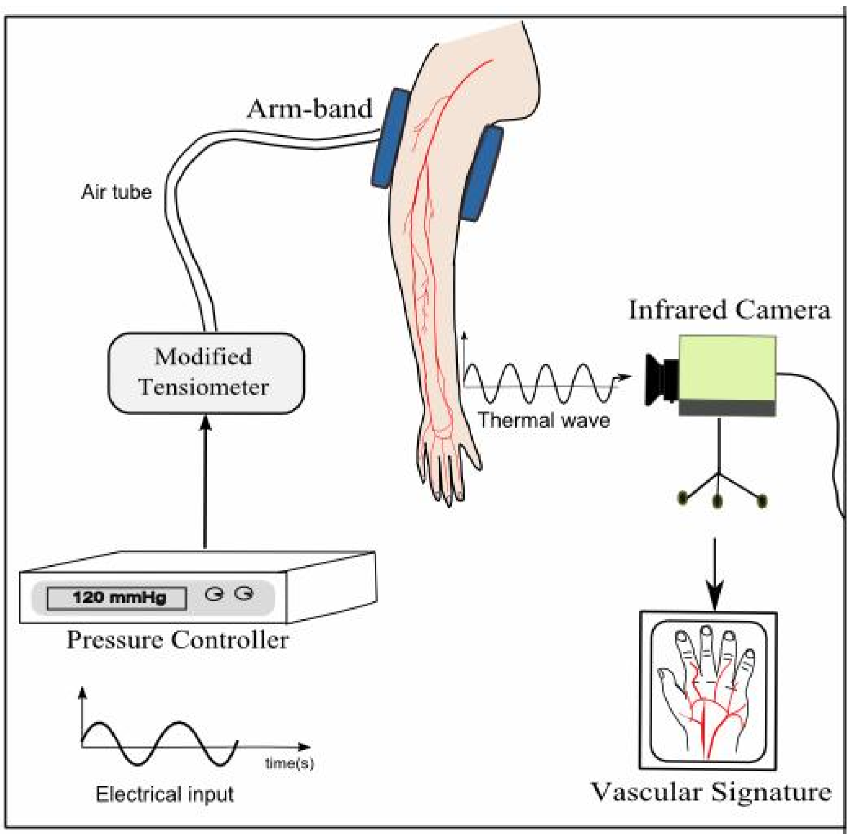


Figure 2 Experimental setup

The duration of each experiment is about 350 seconds. For the hand thermal mapping, an infrared MWIR camera produced by Flir Systems (Phoenix model) is used with a 50 mm lens. The resolution is 640x512 pixels and it operates in the 3.0 to 5.0 µm spectral band. The experiments are carried out after a 10 minute period in order to normalize the body temperature. The pressure perfectly follows the chosen command. One need only to set the minimum and maximum values according to the systolic and diastolic pressure, and choose the frequency of excitation. In this experiment, better results are obtained with a frequency of 0.03 Hz. Since the heat diffusion length is inversely proportional to the square root of the modulation frequency, the penetration depth could be better when choosing a small frequency (**1**):

$$\mu = \sqrt{\frac{2\alpha}{\omega}} = \sqrt{\frac{\alpha}{\pi f}} \qquad (1)$$

where $\alpha = \dfrac{k}{\rho C_p}$ $[m^2/s]$ is the thermal diffusivity, with k $[W/m\ ^\circ C]$ being the thermal conductivity, $\rho\ [kg/m^3]$ is the density, Cp $[J/kg^\circ C]$ the specific heat and f the thermal wave modulation frequency. A software package "IR_View" [7] developed in our laboratory enables interactive processing of thermal image sequences using a graphical interface. It also includes the visualization of the temperature dynamics and profiles in every pixel of the images.

4. RESULTS AND DISCUSSION

The acquisition system calibration is performed with a blackbody. Then, the temperature distribution is given by a two-dimensional image of the human skin obtained by converting the gray level at each pixel with a calibration curve. Knowing the human body temperature range and the room temperature, the calibration was made between 15°C and 50°C.

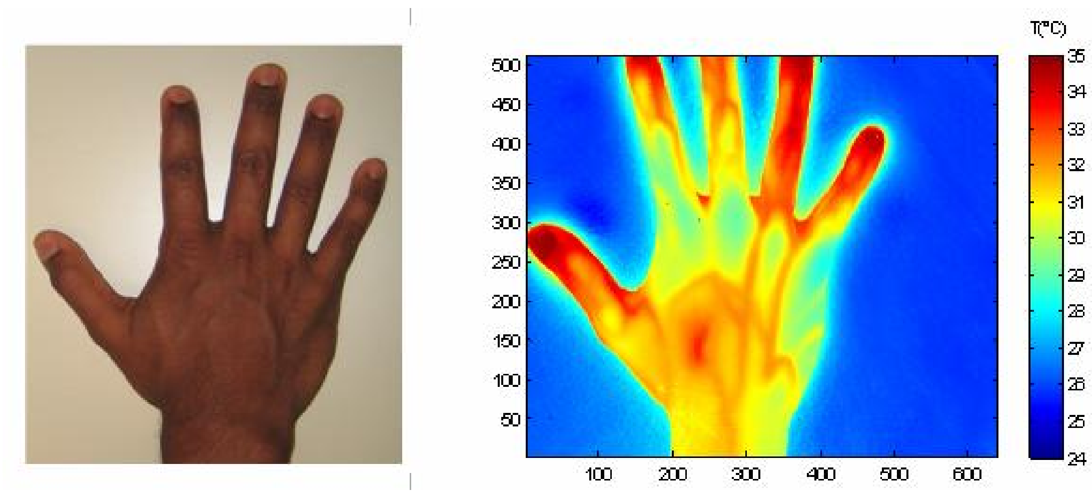


Figure 3 Visible and thermal images of the dorsal hand

As expected, the skin tissue containing veins possesses a temperature gradient. Areas just above the vein emanate light with higher intensity and thus appear as brighter regions in a thermal image [7]. The experiments have shown that the fingers are hotter than the back of the hand, except on the regions just over the veins. The temperature on the image is displayed between 24°C (room temperature) to 35°C corresponding to the highest temperature of the vein pixels for the hand shown in Figure 3.

4.1 Thermal wave profiles

During the experiment, 600 thermal images were acquired with a frequency of 1.71 fps (frames per second). The controlled modulated excitation on the armband generates thermal waves on the back-hand which are captured by the infrared camera. The data are saved in a matrix of dimension [640×512×600]. Thus, a pixel in the image is a vector of 600 elements corresponding to 350 seconds in time according to the acquisition frequency. Since there is a temperature contrast between the vein and the surrounding tissue (ST), one could follow the temporal behavior of the vein pixels (VP) through the whole recorded frames. A wave is then formed in the vein profiles and studied using the Fast Fourier Transform (FFT) of this vector to detect the fundamental harmonics in the blood vessels and the phase shift between the excitation and the resulted wave. The thermal waves are detected especially on the VP profiles. For this study, one considers that the distance between the vein and the surface of the back-hand skin is negligible. Two periodic stimulation waveforms have been investigated: *sine* waveform and sawtooth waveform (Figure 4a. and Figure 5a.).

4.1.1 Sine wave pressure stimulation

In order to modulate the blood circulation, the first tested stimulation was a sine wave pressure with an average value of 110 mmHg (80 to 140 peak-to-peak values). At the end of the experiment, the thermal profile on the VP vectors decreases for about 0.3°C, without taking into account the transient state (see Figure 4).

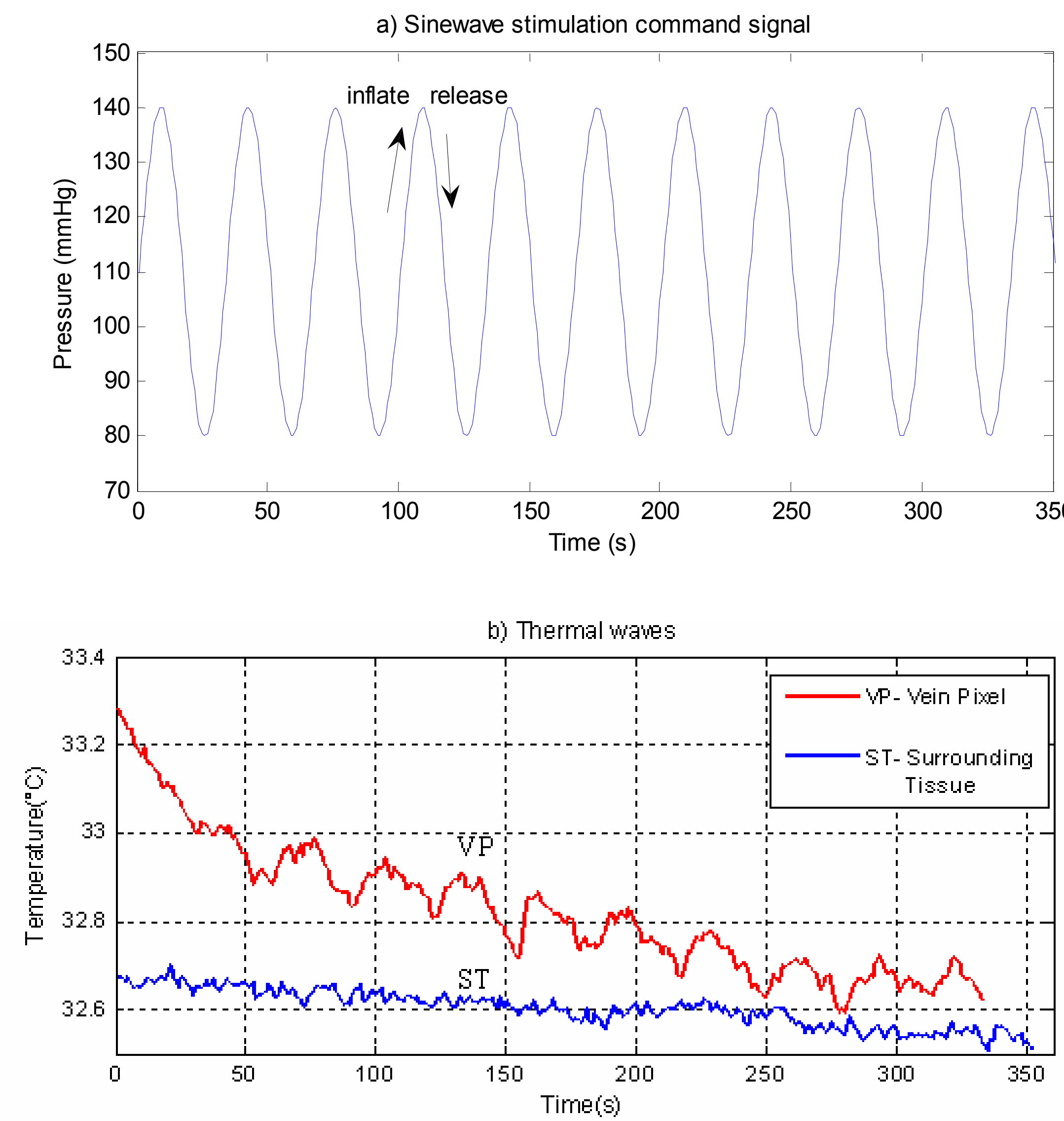


Figure 4 a) Applied sine wave pressure,
b) Thermal wave on a vein pixel (VP) and surrounding tissue (ST)

It can be concluded that since the frequency of modulation is small (0.03 Hz) in order to obtain a clear visualization of the veins, the period of tightening through the armband is relatively long, thus the temperature on the pixels over the vein decreases. Also, the average pressure of 110 mmHg applied on the arm-band might be excessive.

4.1.2 Sawtooth pressure stimulation

To minimize the temperature drop, the excitation frequency must be kept at 0.03 Hz while changing the waveform. A sawtooth excitation with a lower value of the average pressure wave (80 mmHg instead of 110 mmHg) is preferable since it decreases the length of time during which the armband is tightened in comparison with modulating using sine wave stimulation. Therefore, the armband inflates during 33 seconds and the pressure is then released. This sequence is performed 9 times. Furthermore, a minimum pressure fixed at 20 mmHg relaxes the modulation in an adequate way.

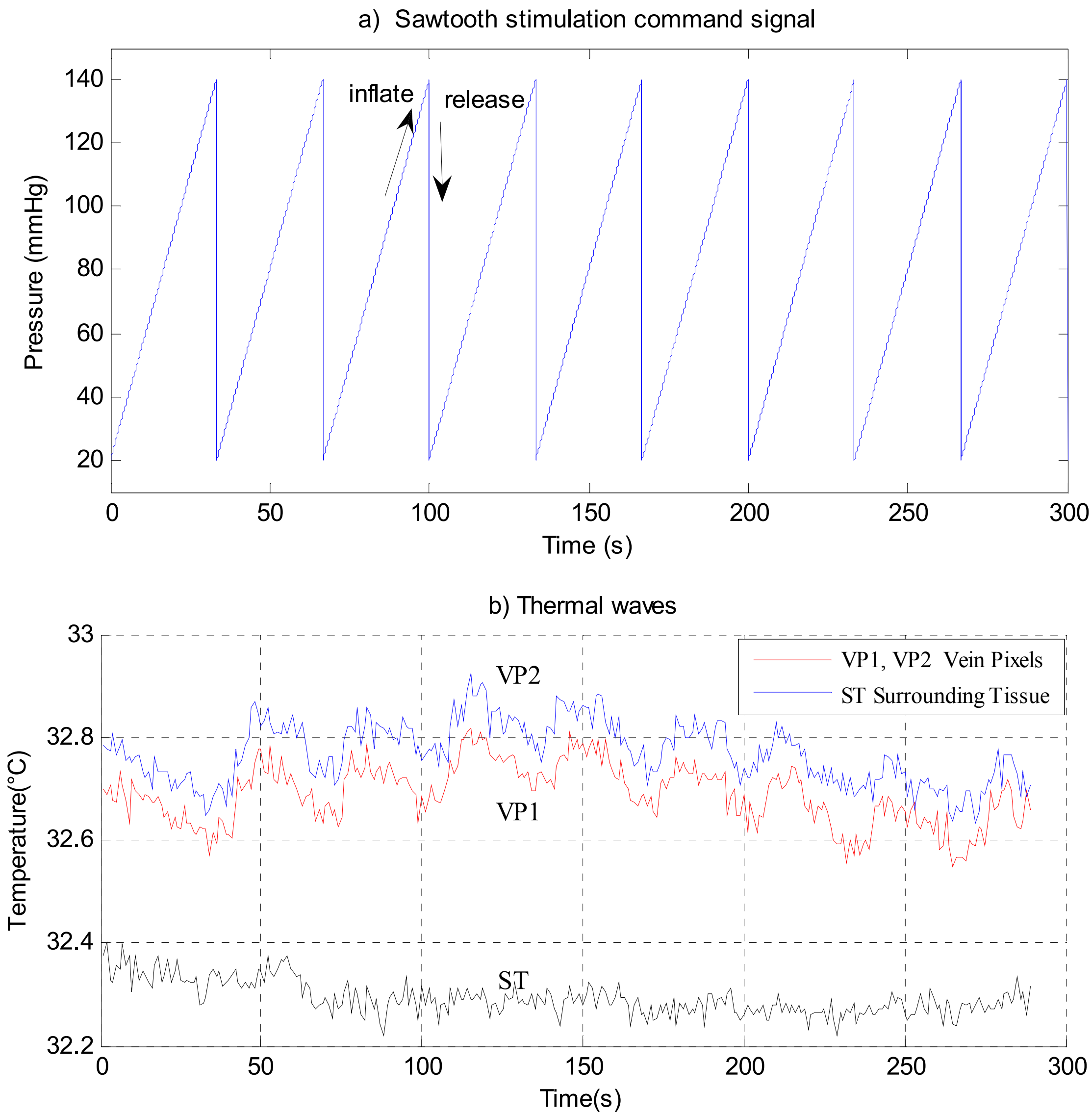


Figure 5 a) Applied sawtooth pressure,
b) Thermal waves on 2 vein pixels VP1, VP2 and Surrounding Tissue ST.

Figure 5 shows that this excitation has a smaller effect on the temperature of the vein pixels. One can see that the VP profiles do not decrease according to the number of excitation cycles, but rather stay relatively constant throughout the experiment.

Therefore, with a sawtooth modulation, the hand surface temperature recovers more quickly than when a sine wave excitation is used. However, the temperature on the surrounding tissue is considered to be relatively constant in both cases.

Moreover, after having obtained the thermal profiles of the pixels located on the areas above the veins, an FFT is applied in order to collect the frequency components contained in the thermal wave. Thus, the frequency of 0.03 Hz corresponding to that used for the modulation is obtained. The spectrums representing the frequencies of the thermal wave (VP1) and the sawtooth excitation are superposed and both illustrated in Figure 6. The signals were first normalized between [0, 1]. The X-axis represents the logarithmic scale. One can observe the strong DC component on the Fourier frequency spectrums due to the non-null average signal, since all the image pixels represent temperature values.

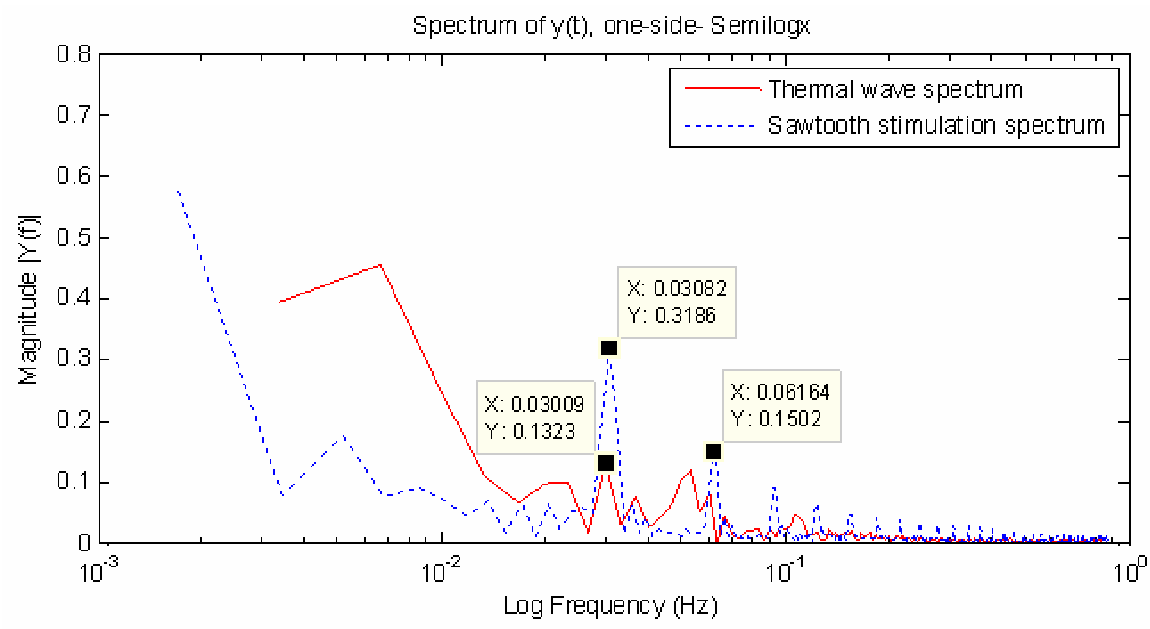


Figure 6 Analyzing FFT Frequency Spectrum of the thermal wave

4.1.3 FFT amplitude of the hand thermal images

During the modulation, a series of 600 images were acquired. A Fast Fourier Transform (FFT) was then applied on the obtained data on every pixel of the images and with respect to time. As described in [10], data can be transformed from the time domain to the frequency spectra (2) using the one-dimensional discrete Fourier transform (DFT):

$$F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t) \exp^{(-j2\pi nk/N)} = \mathrm{Re}_n + \mathrm{Im}_n \qquad (2)$$

where j is the imaginary number (j^2=-1), n designates the frequency increment (n=0,1,…N), Δt is the sampling interval, and *Re* and *Im* are the real and the imaginary parts of the transform, respectively. Real and imaginary parts of the complex transform are used to estimate the amplitude A and the phase ϕ (Eq.3):

$$A_n = \sqrt{\mathrm{Re}_n^2 + \mathrm{Im}_n^2} \qquad and \qquad \phi_n = \tan^{-1}\left(\frac{\mathrm{Im}_n}{\mathrm{Re}_n}\right) \qquad (3)$$

The use of the FFT on thermographic data was first proposed by Maldague and Marinetti in 1996 [11].

Although, in nondestructive testing, generally the phase images which represent a local delay between the excitation and the thermal wave provide more information than the amplitude, in our case, as can be seen in (Figure 7 and Figure 8) the contrast of the vascular tree is more significant on the amplitude images. Therefore, amplitude images are then kept to perform the image processing tool for the quality improvement and the extraction of the vascular signature.

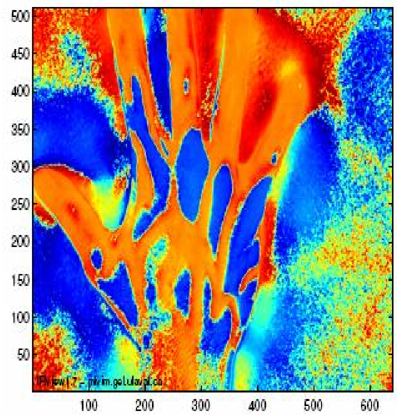


Figure 7 FFT Phase of the hand thermal image

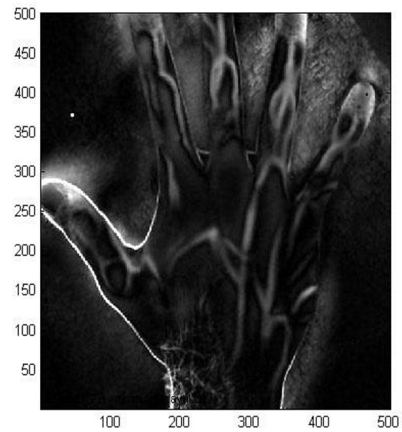


Figure 8 FFT Amplitude of the hand thermal image

Figure 9 illustrates results of a good visualization of the back-hand vascular signature on 2 people of different skin color using the FFT amplitude of the infrared image.

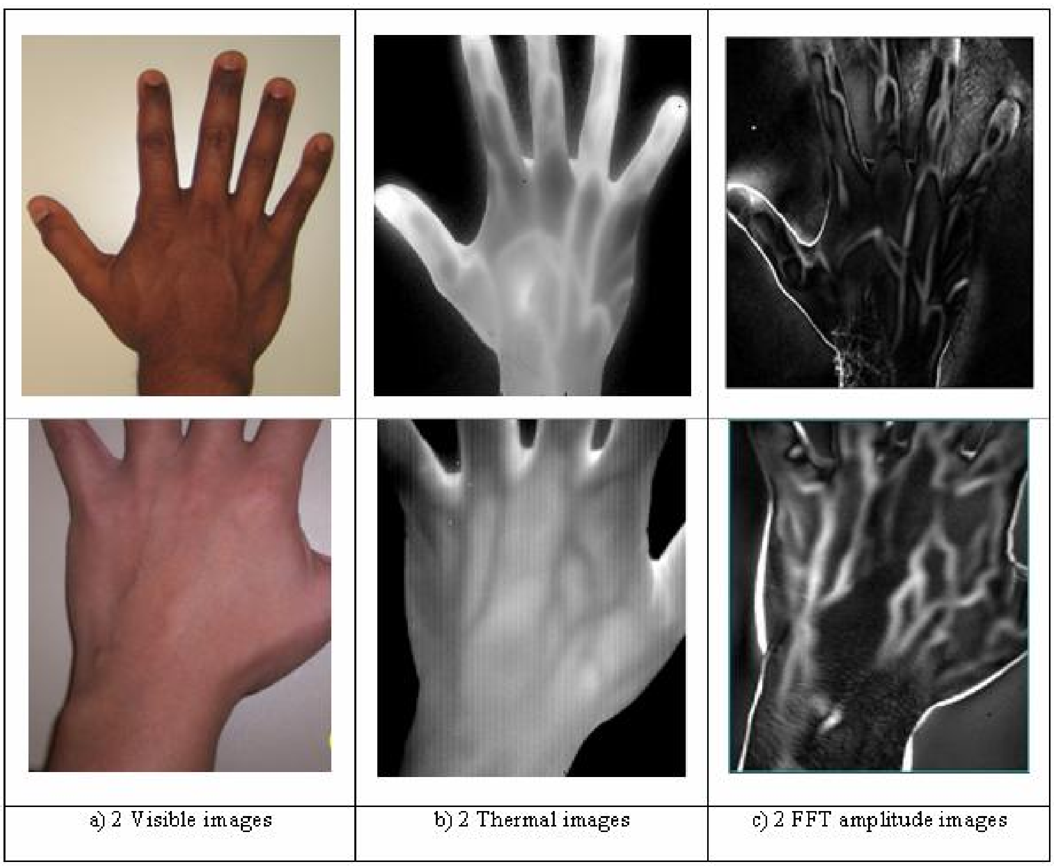


Figure 9 (a, b, c) Results of dorsal hand visualization with the proposed approach on 2 people.

Thus, one can see on this figure the efficiency of infrared thermography to see "*inside*" the cutaneous layer of a human hand, contrary to the vision in the visible spectrum. The contrast between the vascular tree and the surrounding tissue is better while visioning on the thermal images, but much more significant when the FFT is used.

5. IMAGE PROCESSING FOR THE HAND VEIN EXTRACTION

5.1 Color Processing

The thermal images preprocessed with fast Fourier transform are in RGB color format. Tests were conducted in color and grayscale converted images. RGB, HSL and Lab color spaces were used [8]. The tests show that the best results are obtained with the Green color channel when used alone. The remaining experiments were conducted using a Green channel 8 bit image (Figure 10).

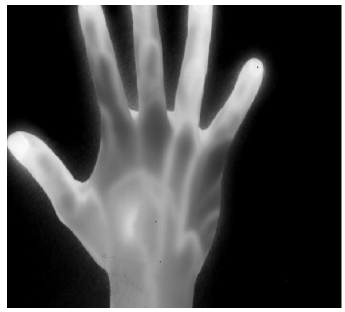


Figure 10 Preprocessed hand image in the Green color channel

5.2 Image enhancement

The images of the dorsal venous network are obtained using a mid-wave thermal camera. Thermal cameras give rise to noisy images. These images must be preprocessed before feature extraction. Anisotropic diffusion was used for contrast enhancement (Figure 11). Nonlinear anisotropic diffusion filters are iterative filters proposed by Perona and Malik [12]. These filters are used for edge preserving image enhancement. The proposed diffusion process encourages intra-region smoothing while inhibiting inter-region smoothing. The mathematical framework for anisotropic diffusion is given by the equations below:

$$\frac{\partial}{\partial t} I(\bar{x},t) = \nabla \bullet (c(\bar{x},t)\nabla I(\bar{x},t)) \quad (4)$$

Where $I(\bar{x},t)$ is the image, $\bar{x}$ represent the image axes (i.e. (x,y)), t refers to the iteration step.

$c(\bar{x},t)$ is called the *diffusion function.* Two functions were proposed for $c(\bar{x},t)$ by Perona and Malik [12]:

$$c_1(\bar{x},t) = \exp\left(-\left(\frac{\left|\nabla I(\bar{x},t)\right|}{\kappa}\right)^2\right) \quad (5)$$

and

$$c_2(\bar{x},t) = \frac{1}{1+\left(\frac{\left|\nabla I(\bar{x},t)\right|}{\kappa}\right)^{1+\alpha}} \quad \left|\alpha > 0\right. \quad (6)$$

κ is the *diffusion constant* or the *flow constant*.

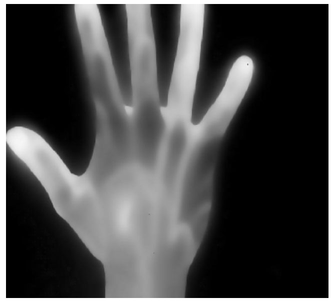


Figure 11 Contrast enhanced image with anisotropic diffusion.

5.3 Features extraction

Features representing important components of the dorsal venous network of the hand are extracted from the enhanced image. We use mathematical morphology to process the image and extract the subcutaneous blood vessels. First we use top hat and bottom hat transforms to extract the desired features using a suitable structuring element B that is bigger than the width of the subcutaneous vessels in the image [13]. For the MWIR thermal images, we subtract the two obtained images (Figure 12).

The top hat and bottom hat transforms are given below:

$$TopHat(I,B) = I - (I \circ B) = I - \max_B(\min_B(I)) \qquad (7)$$

$$BottomHat(I,B) = (I \bullet B) - I = \min_B(\max_B(I)) - I \qquad (8)$$

Where: $\circ$ is a morphological opening operation.
$\bullet$ is a morphological closing operation.

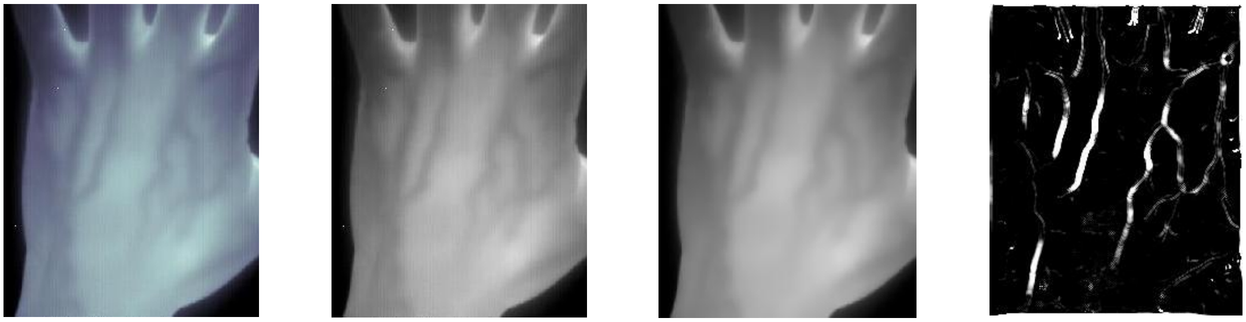
5.4 Thresholding

A simple image binarization is used. A manual threshold Th is selected for the processed images and applied in order to obtain the binarized image.

$$I_{bin} = 1 \; if \; I(x,y) > Th, \; else \; I_{bin} = 0 \qquad (9)$$

Figure 12 Physiological features extraction with morphological filtering

Figure 13 (a, b, c and d) shows other results of hand vein extraction with the presented image processing tool.



a. Thermal RGB image b. Thermal Green channel c. Anisotropic diffusion d. Differential top-Hat filtering

Figure 13 Other Results of morphological filtering

6. CONCLUSION

The overall goal of this work is to visualize the subcutaneous skin of the back-hand and its vascular tree to help in the diagnosis of certain vein diseases and also to build a database for hand vein identification. We have introduced a method to visualize the vein pattern using lock-in thermography. We studied the thermal behavior of some pixels on the areas above the veins. Periodic thermal waves were found in the thermal profiles while following principally the veins on the infrared image. At the beginning, we used a periodic sinewave excitation to modulate blood circulation. But it was noted that, after a few minutes, the thermal profiles tend to fall about 0.3 °C. Then, we applied a sawtooth excitation and we obtained better results concerning the temperature evolution on the vein pixels.

Using the FFT amplitude of the infrared images, the contrast between the structure of the veins and the surrounding tissue is more significant then while working on the original thermogram alone. Thus, the study of the profile behavior becomes much easier. The figures presented here indicate that the results are promising especially since no extra light source or harmful radiation on the body was required. Combining these results corresponding to the vein structure on the hand or on the legs (varicose veins) with clinical data can enable an evaluation of the veins as either '*normal or pathological'*. Moreover, a series of tests can be used to build a database for the biometric identification of the dorsal hand vascular system.

ACKNOWLEDGMENTS

The authors wish to express their sincere appreciation to the reviewers who have contributed their efforts to reviewing this paper and they gratefully acknowledge people who accepted to participate to the experiments.

REFERENCES

1. X. Maldague, "Theory and Practice of infrared technology for nondestructive testing", *Wiley-interscience (2001*), ISBN 0-471-18190-0.
2. V. Vavilov et al. "Statistical analysis of the human body temperature asymmetry as the basis for detecting pathologies by means of IR thermography", *Proc. SPIE Vol*. 4360, 2001, 482-491.
3. B. Jung, et al., "Usefulness of thermovision in venous system pathology", *Proc. QIRT'2000, pp.* 393-398, France, 2000.
4. D. Wu, H. Hamann, A. Salerno, G. Busse, "Lock-in thermography for imaging of modulated flow in blood vessels", in*: Quantitative Infrared Thermography, QIRT 96*, Pisa, 1997, pp. 343–347.
5. V. Paquit, J. Price et al. "Combining near-infrared illuminants to optimize venous imaging", *SPIE Medical Imaging 2007*: Visualization, Image-Guided Procedures, and Display, 17–22 February 2007, San Diego, Ca, USA, 2007.

6. C. Liukui, Z. Hong, L. Li, X. Peng and L. Shuo, "Near-Infrared Dorsal Hand Vein Image Segmentation by Local Thresholding Using Grayscale Morphology" *in Proc.: Bioinformatics and Biomedical Engineering, ICBBE pp.* 868-871, 6-8 July 2007.
7. M. Klein, http://irview.m-klein.com, Laboratoire de vision et systèmes numériques, Dép. de génie électrique, Université Laval, Québec City, Québec, Canada, G1K 7P4, Last Update : 03-2007.
8. A. Nadort, *"*The Hand Vein Pattern Used as a Biometric Feature*", Master Literature Thesis*, May 2007- Amsterdam.
9. http://www.snv.jussieu.fr/bmedia/ATP/pressio.htm Jussieu Biology and Multimedia web site, viewed on September 5th 2007.
10. C. Ibarra-Castanedo, J-M. Piau, S. Guibert, X. P. Maldague and A. Bendada "Chapter 14. Active infrared thermography techniques for the nondestructive testing of materials," in *Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization*, C. H. Chen Ed., pp. 325-348, 2006.
11. X. P. Maldague and S. Marinetti "Pulse Phase Infrared Thermography," *J. Appl. Phys.*, **79**(5):2694-2698, 1996.
12. P. Perona, J. Malik, "Scale-space and edge detection using anisotropic diffusion". IEEE Trans. on Pattern Analysis and Machine Intelligence. Vol.12. Num. 7. pp. 629—639 (1990)
13. R.C. Gonzalez, R.E. Woods: "Digital Image Processing". 2nd Edition, Prentice Hall (2002)