http://doi.org/10.35784/iapgos.6759

received: 26.10.2024 | revised: 18.03.2025 | accepted: 20.03.2025 | available online: 31.03.2025

DESIGN AND IMPLEMENTATION OF A VEIN DETECTION SYSTEM FOR IMPROVED ACCURACY IN BLOOD SAMPLING

Omar Boutalaka[1], Achraf Benba[1], Sara Sandabad[2]

[1]Mohammed V University in Rabat, Electronic Systems, Sensors and Nanobiotechnologies (E2SN), High National School of Arts and Crafts (ENSAM), Rabat, Morocco, [2]Higher Institute of Maritime Studies (ISEM), Casablanca, Morocco

Abstract. *Blood sampling is a routine procedure in medical diagnostics, yet precise vein visualization methods remain limited. This project introduces a system designed to improve vein detection during blood collection. It relies on Near-Infrared (NIR) light, which interacts with the skin and highlights veins by taking advantage of hemoglobin's infrared absorption properties. Using a Raspberry Pi and an infrared camera, image acquisition and processing are handled through MATLAB and Python algorithms, which allow real-time visualization of veins. The system has been tested on a database of infrared images of hands and arms, effectively enhancing vein contrast in real time. The display is connected to the Raspberry Pi, giving medical staff a visual guide. This technology aims to streamline procedures for healthcare professionals, including doctors, nurses, and medical students, particularly in high-volume settings like labs and blood transfusion centers where vein visualization is critical to patient care.*

Keywords: NIR, vein detection, image processing, embedded system

PROJEKTOWANIE I WDROŻENIE SYSTEMU DETEKCJI ŻYŁ W CELU ZWIĘKSZENIA DOKŁADNOŚCI POBIERANIA KRWI

Streszczenie. *Pobieranie krwi jest rutynową procedurą w diagnostyce medycznej, jednak precyzyjne metody wizualizacji żył pozostają ograniczone. Projekt ten wprowadza system mający na celu usprawnienie wykrywania żył podczas pobierania krwi. Opiera się na świetle bliskiej podczerwieni (NIR), które oddziałuje ze skórą i uwydatnia żyły, wykorzystując właściwości absorpcji podczerwieni przez hemoglobinę. Przy użyciu Raspberry Pi i kamery na podczerwień akwizycja i przetwarzanie obrazu odbywa się za pomocą algorytmów MATLAB i Python, które umożliwiają wizualizację żył w czasie rzeczywistym. System został przetestowany na bazie danych obrazów dłoni i ramion w podczerwieni, skutecznie zwiększając kontrast żył w czasie rzeczywistym. Wyświetlacz jest podłączony do Raspberry Pi, zapewniając personelowi medycznemu wizualne wskazówki. Technologia ta ma na celu usprawnienie procedur stosowanych przez pracowników służby zdrowia, w tym lekarzy, pielęgniarki i studentów medycyny, szczególnie w środowiskach o dużym natężeniu ruchu, takich jak laboratoria i centra transfuzji krwi, gdzie wizualizacja żył ma kluczowe znaczenie dla opieki nad pacjentem.*

Słowa kluczowe: NIR, wykrywanie żył, przetwarzanie obrazu, system wbudowany

Introduction

Blood sampling is a fundamental procedure in medical diagnostics, with billions of samples collected annually worldwide. Despite its widespread use, this process often lacks precise methods for vein visualization, posing a significant challenge for healthcare providers. Difficulty in locating veins accurately can lead to multiple puncture attempts, causing stress and discomfort for both patients and medical staff. This challenge is particularly acute for vulnerable populations, such as young children, the elderly, and patients undergoing treatments like chemotherapy or radiotherapy, where veins may be less visible or accessible.

To enhance the success and efficiency of blood draws, this project focuses on developing a real-time vein detection system based on infrared imaging technology. By leveraging the properties of near-infrared (NIR) light, this system aims to improve vein visibility, reduce the risks associated with unsuccessful punctures, and streamline the sampling process. The design takes advantage of the unique absorption characteristics of deoxygenated hemoglobin in the NIR spectrum, enabling clearer visualization of veins relative to surrounding tissue. This approach not only increases the accuracy of venipuncture but also enhances patient comfort and minimizes procedural time.

The cardiovascular system, consisting of the heart, blood vessels, and lymphatic vessels, plays a central role in transporting nutrients and oxygen throughout the body. This closed-circuit network carries blood to and from the heart, supplying cells with essential substances and removing metabolic waste. Key components of this network, including veins and capillaries, are critical targets in blood sampling but can be challenging to locate, especially in patients with deep or narrow veins.

Currently, several imaging techniques are available for vascular visualization, though each has limitations that make it impractical for routine venipuncture. Angiography and phlebography use contrast agents and X-rays to visualize blood vessels but are generally limited to hospital settings and involve radiation exposure [7, 12]. Venous Echo-Doppler employs ultrasound technology for real-time imaging of blood flow, though it lacks the depth of visualization necessary for precise vein mapping [6]. CT angiography and Angio-MRI provide high-resolution vascular imaging but require specialized equipment, limiting their accessibility in everyday medical settings [14, 9]. Venous rheo-plethysmography measures impedance changes to diagnose venous abnormalities, yet does not directly visualize veins for puncture [11].

In light of these limitations, our project proposes a vein detection system using near-infrared imaging to provide real-time, clear visualization of veins. By harnessing NIR light, which is selectively absorbed by deoxygenated hemoglobin, the system enhances vein contrast, facilitating more efficient and accurate blood sampling. The system incorporates Raspberry Pi technology with infrared LEDs and a camera, along with image processing algorithms in MATLAB and Python, to create a portable, accessible tool that can be easily used by healthcare professionals.

This project bridges the gap between advanced imaging techniques and practical clinical needs, offering a user-friendly solution that enhances the accuracy of blood vein detection and improves the overall patient experience.

1. Material and methodology

The human skin comprises multiple components, including fat, veins, arteries, and nerves. As illustrated in Figure 1, when skin interacts with infrared light, phenomena such as absorption, diffusion, and reflection occur across its various layers. For this project, we employ Near Infrared (NIR) technology, specifically targeting the spectral range between 780 nm and 950 nm due to its optimal penetration depth, reaching up to 3 mm beneath the skin where veins are located.

This range allows us to exploit the properties of chromophores, which absorb light within specific wavelength bands and produce color effects. Key chromophores in blood include water, oxygenated hemoglobin (in arterial blood), and deoxygenated hemoglobin (in venous blood). Among these, deoxygenated hemoglobin absorbs more radiation than other tissues at wavelengths under 780 nm, while water absorption dominates above 950 nm. Thus, NIR light from our source interacts with skin and fat, which primarily scatter the light, while blood absorbs it due to hemoglobin's properties. This contrast results in a clearer view of veins as dark regions against the lighter appearance of skin and fat.

For our vein visualization system, the patient's skin is exposed to NIR (Near Infrared) light, provided through an array of LEDs. Due to the unique absorption properties of deoxygenated hemoglobin (Hb) in venous blood, NIR radiation is absorbed more significantly by veins compared to surrounding tissues like skin and muscle. A Raspberry Pi [13], connected to a NoIR camera, serves as the primary acquisition device. The acquired data then undergoes various filtering and processing stages in MATLAB and Python to produce visual results displayed on a screen.

In our project, we employ a near-infrared light source achieved through either an 850 nm LED matrix panel, with each LED rated at 2W, or a custom LED circuit on a prototyping board, adjustable for optimal infrared output. The imaging system uses a 5-megapixel Pi camera (OV5647 model), devoid of an infrared filter (NoIR), which connects via the CSI interface with an FFC cable. The high-speed data transmission via the CSI bus enhances image clarity, allowing a rapid flow of graphic data. The camera module itself is compact (25 mm × 24 mm) and lightweight (~30 g) with a fixed-focus lens (focal length of 3.6 mm and aperture of f/1.8).

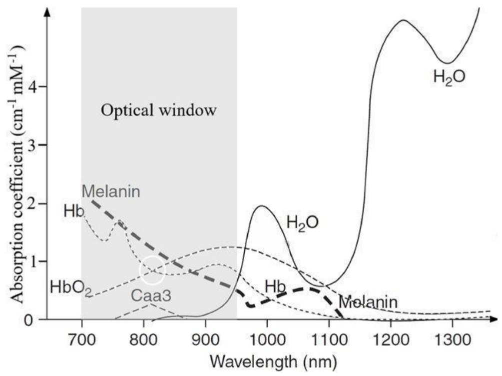

Fig. 1. The absorption spectra of water (H_2O), deoxyhemoglobin (Hb) and hemoglobin (hbo2) [2]

A comprehensive database of venous images from various individuals was compiled using the infrared camera linked to the Raspberry Pi, enabling robust testing of our processing algorithms. After image acquisition, data is transferred to a computer where MATLAB processes the images to enhance visualization, reducing noise and highlighting critical features like edges. The image enhancement process includes the application of filters, each affecting individual pixels by considering neighboring pixels to improve the overall image through denoising and smoothing. Effective filter use requires a thorough understanding of the algorithm and its parameters. Spatial filters are defined by [1]:

- filter support, which refers to the neighborhood's size and shape,
- the central pixel's position within the support,
- the algorithm to compute output values based on neighborhood values.

Edge detection is then performed to highlight essential structural elements of the object, which may arise from depth discontinuities or reflectance properties. Among the various edge detection methods, two main approaches are commonly used: one based on the gradient extremums of the intensity function and another that identifies zero-crossings in the second derivative, often employing the Laplacian or other nonlinear expressions.

To achieve optimal results in our project, we apply multiple filters to determine the most effective processing algorithm. These include:

- The median filter, a spatial filter that calculates the average gray levels of the pixels within a sliding window, similar to convolution, which effectively reduces impulse noise while preserving edges and lines [15].
- The Laplacian filter, which detects zero-crossings in the second derivative for edge enhancement [10].
- The Prewitt filter, which applies horizontal filtering to highlight vertical edges [3].
- The Sobel filter, which applies vertical filtering to highlight horizontal edges [4].

Through this multi-faceted approach, our vein visualization system improves the accuracy and efficiency of vein location, ultimately facilitating procedures for medical personnel in various healthcare settings [8].

2. Results and discussions

Following initial image acquisition, as presented in Figure 2, we evaluated multiple filtering techniques, including the Laplacian, Sobel, and Prewitt filters. These edge-detection filters, while useful for highlighting contours, introduced substantial noise into the processed images. This noise degraded image clarity by emphasizing non-vascular structures and obscuring the targeted venous patterns. The Laplacian filter, in particular, amplified high-frequency noise, leading to exaggerated textures in skin regions, while the Sobel and Prewitt filters highlighted edges excessively, which reduced the overall quality and interpretability of the image.

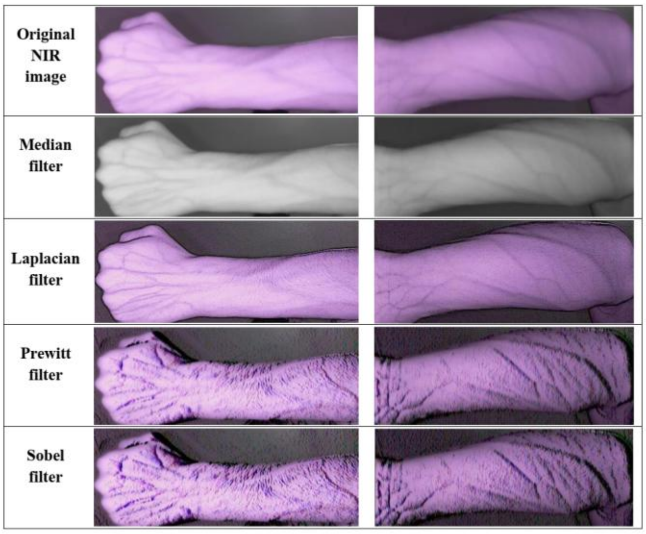

Fig. 2. The obtained results using different filters

In contrast, the application of the median filter achieved a substantial reduction in noise without sacrificing image detail, specifically preserving the edges associated with venous structures. Unlike linear filters, which may blur important boundaries, the median filter is a non-linear technique that replaces each pixel value with the median value of neighboring pixels. This technique is particularly effective in suppressing impulse noise and small, isolated artifacts without distorting the overall structure. The median filter's ability to retain essential edge details while eliminating noise made it the optimal choice for our project, as it effectively isolated vein patterns from extraneous textures, providing a cleaner foundation for further processing.

Once noise reduction was achieved, the next phase involved adaptive histogram equalization to amplify the contrast of venous structures. Histogram equalization is a grayscale transformation method that enhances image contrast by redistributing pixel intensities across the entire dynamic range of the image, producing a more balanced intensity distribution that brings out subtle details. In the context of vein visualization, this contrast enhancement is crucial, as it maximizes the visibility of veins that might otherwise blend into surrounding tissues.

We employed CLAHE (Contrast Limited Adaptive Histogram Equalization), an advanced technique specifically designed to prevent over-amplification of noise in uniform areas, which is a common drawback in traditional histogram equalization. CLAHE operates by dividing the image into small, localized sections (or tiles) and applying histogram equalization within each section independently. To avoid artifacts or excessive contrast in homogenous regions, CLAHE limits the contrast based on a predefined threshold. This controlled contrast enhancement proved particularly effective for veins, where subtle differences in tissue density and chromophore concentration could now be more distinctly visualized. The use of CLAHE not only improved vein clarity but also provided a more balanced image that highlighted vascular features without overwhelming artifacts. Figure 3 demonstrates the improved contrast achieved through CLAHE, along with histograms showing pixel intensity distributions before and after processing.

To validate the robustness of our approach, we tested the system on a dataset containing venous images from a diverse sample of individuals across various age groups, skin types, and genders. This diversity ensured that the system could adapt to physiological variations such as skin thickness, melanin concentration, and vascular structure, which impact infrared absorption and reflectance differently. As shown in Figure 4, the enhanced contrast consistently highlighted veins across all samples, confirming the system's adaptability and reliability.

For practical application, particularly in medical environments requiring immediate access to veins (e.g., emergency departments, blood donation centers), we developed a real-time simulation using Python. This simulation incorporates the complete image processing pipeline, from initial image acquisition and filtering to CLAHE-based contrast enhancement. By optimizing each step, our Python-based program achieves real-time processing, allowing healthcare personnel to visualize veins directly on a connected display. This real-time feedback is essential in fast-paced medical settings where swift and accurate vein access can significantly impact patient outcomes.

In the final stages, we implemented edge detection algorithms to further emphasize venous structures, isolating them from surrounding tissues for enhanced clarity. Edge detection is a critical step in image processing, often used to outline significant structures within an image by identifying intensity changes, which represent transitions between different tissue types. In our system, we explored various edge detection methods as cited earlier.

By combining the median filter's noise suppression with the Sobel and Prewitt filters' orientation-based edge enhancements, we refined the visual representation of veins, creating a more cohesive image with reduced artifacts. Edge detection also facilitates automated recognition of veins by enhancing their boundaries, which could be particularly valuable for future integration with automated venous access tools.

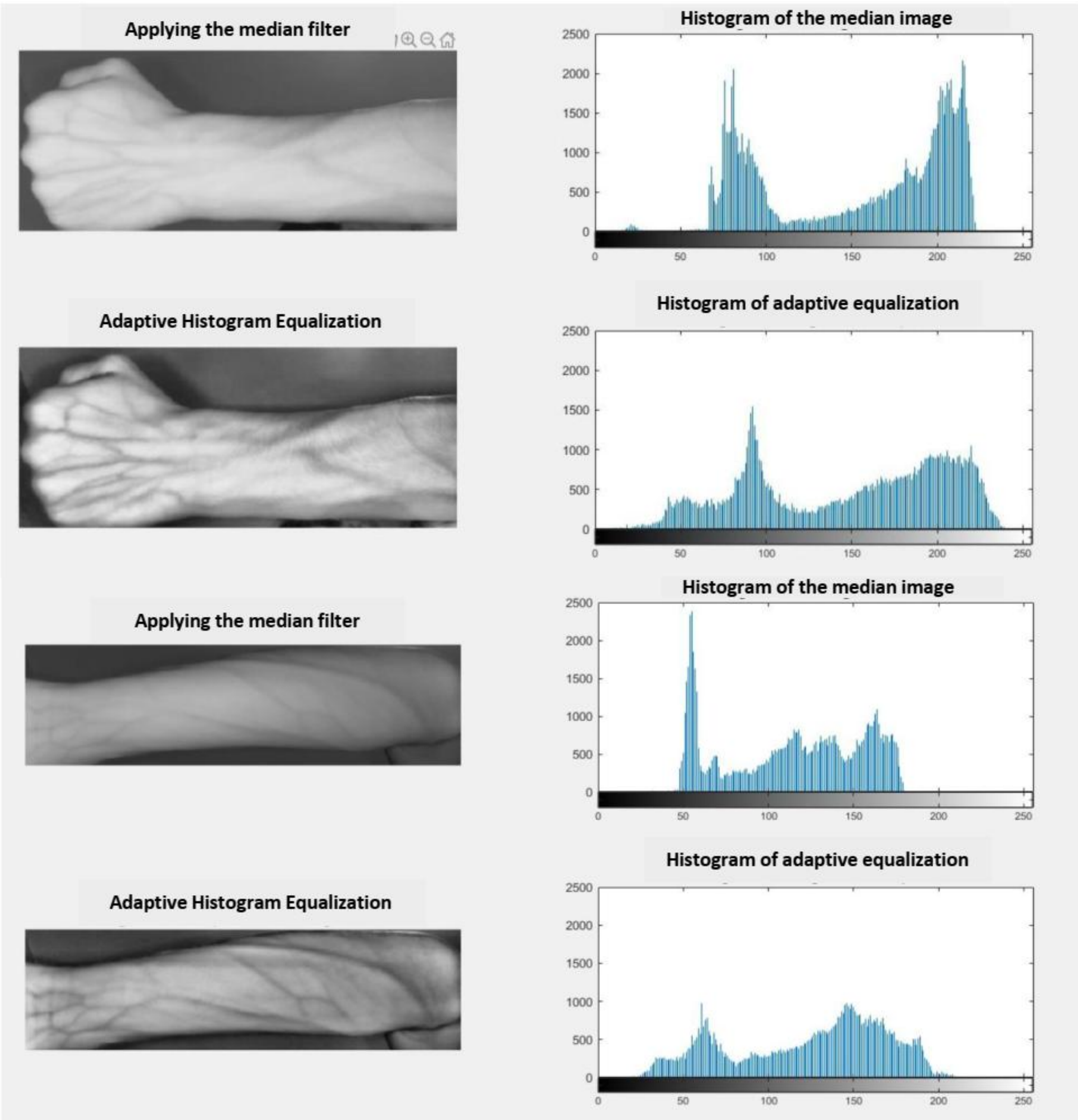

Fig. 3. Results after using adaptive histogram equalization

The completed vein visualization system, utilizing median filtering and CLAHE-based histogram equalization, represents a significant advancement in vein localization technology. Through iterative testing and optimization, our system reliably increases contrast and isolates vein patterns, facilitating clear vein visualization that aids in medical procedures. This setup has demonstrated effectiveness across a broad demographic range, proving its adaptability in real-world conditions.

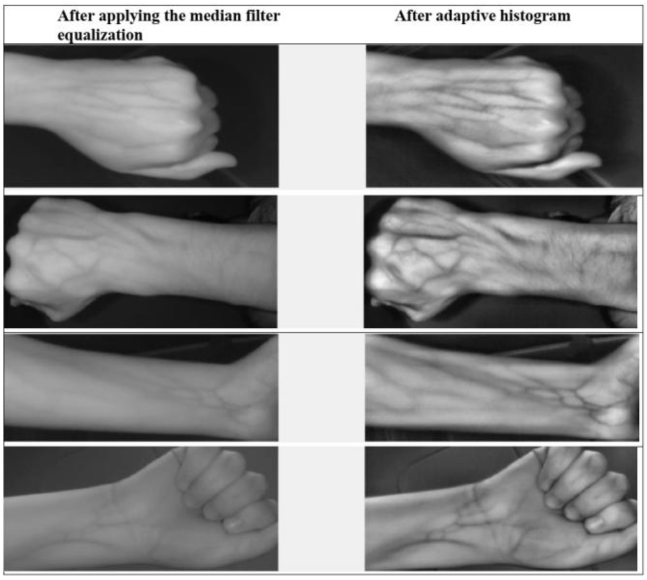

Fig. 4. Results after applying the median filter and after adaptive histogram equalization

3. Conclusion

Image processing has become an invaluable tool in medicine, particularly in diagnostics, due to its capability to transform images for extracting vital information. Leveraging platforms like MATLAB and Python, medical imaging can enhance diagnostic accuracy and streamline clinical procedures. In this project, we developed a real-time vein detection system designed to minimize challenges associated with venipuncture by harnessing the properties of infrared light. This work allowed us to integrate and apply various interdisciplinary skills acquired throughout our academic journey, including project management, image processing, programming, risk management, and market analysis. Additionally, it provided a practical opportunity to deepen technical skills, especially with hardware like the Raspberry Pi. To validate our system, we constructed a dedicated database of infrared images collected via an infrared camera, which served as a foundation for testing our vein detection algorithms based on filtering, segmentation, and contrast enhancement. By utilizing this custom database, we were able to rigorously assess the system's efficacy, consistently achieving satisfactory results across multiple testing phases. We then extended these efforts into real-time processing, ensuring that our algorithms could operate effectively under real-world conditions. Through this project, we have not only advanced our technical proficiency in medical imaging and hardware-software integration but have also contributed to the development of a practical tool that can significantly aid healthcare professionals in improving the accuracy and ease of venous access.

References

[1] Aboshosha A. et al.: Image denoising based on spatial filters, an analytical study. International Conference on Computer Engineering & Systems. IEEE, 2009, 245–250.
[2] Almajidy R. K. et al.: A newcomer's guide to functional near infrared spectroscopy experiments. IEEE Reviews in Biomedical Engineering 13, 2019, 292–308.
[3] Amritha P. P., Induja K., Rajeev K.: Active warden attack on steganography using Prewitt filter. International Conference on Soft Computing Systems. Springer, New Delhi 2016, 591–599.
[4] Aqrawi A. A., Boe T. H.: Improved fault segmentation using a dip guided and modified 3D Sobel filter. Society of Exploration Geophysicists Technical Program Expanded Abstracts 2011, 999–1003.
[5] Brownrigg D. R.: The weighted median filter. Communications of the ACM 27(8), 1984, 807–818.
[6] Di Franco M. et al.: Diastolic function abnormalities in rheumatoid arthritis. Evaluation by echo Doppler transmitral flow and pulmonary venous flow: relation with duration of disease. Annals of the Rheumatic Diseases 59(3), 2000, 227–229.
[7] Dumoulin C. L., Hart Jr. H. R.: Magnetic resonance angiography. Radiology 161(3), 1986, 717–720.
[8] Gomes D. M.: Contrast enhancement in digital imaging using histogram equalization. Doctoral dissertation. Université Paris-Est, 2014.
[9] Gómez E. et al.: Diagnosis of thoracic outlet syndrome by angio-MRI. Radiologia 48(5), 2006, 295–300.
[10] Kong H., Akakin H. C., Sarma S. E.: A generalized Laplacian of Gaussian filter for blob detection and its applications. IEEE Transactions on Cybernetics 43(6), 2013, 1719–1733.
[11] Okhnyanskaya L. G. et al.: Assessment of the human regional cerebral blood flow by venous occlusion rheoplethysmoencephalography. Bulletin of Experimental Biology and Medicine 82(5), 1976, 1755–1758.
[12] Thomas M. L.: Phlebography. Archives of Surgery 104(2), 1972, 145–151.
[13] Upton E., Halfacree G.: Raspberry Pi User Guide. John Wiley & Sons, 2014.
[14] Zeman R. K. et al.: CT angiography. AJR. American Journal of Roentgenology 165(5), 1995, 1079–1088.

Ing. Omar Boutalaka
e-mail: omar.boutalaka1999@gmail.com

Omar Boutalaka is currently an application engineer in medical imaging, specializing in the "X-Ray" modality. He obtained his engineering degree in Biomedical Engineering and Hospital Instrumentation from the École Normale Supérieure de l'Enseignement Technique in Rabat in July 2021.

https://orcid.org/0009-0007-5524-6197

Prof Achraf Benba
e-mail: a.benba@um5r.ac.ma

Received the Ph.D. degree in electrical engineering from ENSAM, Mohammed V University, Rabat, Morocco, in 2017. He is a member of E2SN teamsat ENSAM, Mohammed V University. His interests are in speech processing for detectingpeople with neurological disordersand cardiac.

https://orcid.org/0000-0001-7939-0790

Prof. Sara Sandabad
e-mail: sandabad@isem.ac.ma

Received the B.Sc. and the M.Sc. degrees in Electrical Engineering from ENSET, Mohamed V University of Rabat (Morocco) and the Ph.D. degree from ENSIAS from the Mohamed V University of Rabat, all in Electrical Engineering, in 2010, 2012, and 2016, respectively. Currently, she is a professor of Electrical Engineering at ISEM, Hassan II University of Casablanca. She is also an academic member of Laboratory of Control and Mechanical Characterization of Materials and Structures, ENSEM, Hassan II University of Casablanca, Morocco.

https://orcid.org/0000-0002-0813-6178