

ADAPTIVE FILTERING FOR NOISE REDUCTION IN PHOTOPLETHYSMOGRAPHY SIGNALS

Hicham Loumissi^{1,2}, Adil Barra¹, Najat Messaoudi¹, Othmane El Badlaoui², Bahloul Bensassi¹,
Hicham Medromi²

¹Hassan II University of Casablanca, Faculty of Sciences, Industrial Engineering, Data Processing and Logistic Laboratory, Casablanca, Morocco, ²Foundation for Research, Development and Innovation in Science and Engineering, Casablanca, Morocco

Abstract. This article presents an innovative hybrid filtering approach applied to photoplethysmography (PPG) signals, based on the Pulse-sensor, widely used in physiological monitoring devices. The sensor combines hardware functionality, including conventional analogue filtering based on resistor and capacitor net-works, with the ability to access raw signals via a digital interface. To take full advantage of this capability, we designed a soft filtering system fully implemented in the MATLAB development environment. This digital filtering enables real-time processing of photodiode data, bypassing the limitations inherent in fixed analogue filtering. By combining the advantages of both approaches – hardware robustness and software flexibility – our hybrid system improves PPG signal quality, notably by reducing artefacts linked to motion and ambient noise. The performance of this method has been evaluated through a series of test bench experiments, demonstrating a significant improvement in the accuracy of physiological parameter extraction. This re-search opens up new prospects for the development of intelligent, reliable wearable devices for continuous health monitoring in a variety of clinical and ambulatory settings.

Keywords: photoplethysmography (PPG), hybrid filtering, heart rate monitoring, signal processing, pulse-sensor

ADAPTACYJNA FILTRACJA W CELU REDUKCJI SZUMÓW W SYGNAŁACH FOTOPLETYZMOGRAFIK

Streszczenie. W niniejszym artykule przedstawiono innowacyjne podejście do filtrowania hybrydowego sygnałów fotopletyzmoграфicznych (PPG), oparte na czujniku tętna, szeroko stosowanym w urządzeniach do monitorowania parametrów fizjologicznych. Czujnik łączy w sobie funkcjonalność sprzętową, w tym konwencjonalne filtrowanie analogowe oparte na sieciach rezystorów i kondensatorów, z możliwością dostępu do surowych sygnałów poprzez interfejs cyfrowy. Aby w pełni wykorzystać tę możliwość, zaprojektowaliśmy system filtrowania programowego w całości zaimplementowany w środowisku programistycznym MATLAB. To filtrowanie cyfrowe umożliwia przetwarzanie danych z fotodiod w czasie rzeczywistym, omijając ograniczenia związane ze stałym filtrowaniem analogowym. Łącząc zalety obu podejść – niezawodność sprzętu i elastyczność oprogramowania – nasz system hybrydowy poprawia jakość sygnału PPG, zwłaszcza poprzez redukcję artefaktów związanych z ruchem i szumem otoczenia. Skuteczność tej metody została oceniona w serii eksperymentów laboratoryjnych, wykazujących znaczną poprawę dokładności ekstrakcji parametrów fizjologicznych. Badania te otwierają nowe perspektywy dla rozwoju inteligentnych, niezawodnych urządzeń do noszenia, służących do ciągłego monitorowania stanu zdrowia w różnych warunkach klinicznych i ambulatoryjnych.

Słowa kluczowe: fotopletyzmoграфия (PPG), filtrowanie hybrydowe, monitorowanie tętna, przetwarzanie sygnałów, czujnik tętna

Introduction

Photoplethysmography is a non-invasive technique widely used to measure physiological parameters such as heart rate and blood oxygen saturation. The Pulse sensor, equipped with infrared and red LEDs and a photodetector, is a popular choice for these applications due to its ability to detect variations in light absorption by haemoglobin during blood circulation. However, PPG signals are often affected by motion artefacts and ambient noise, which can compromise the accuracy of physiological analyses. To overcome these limitations, we present an innovative hybrid filtering approach that combines conventional analogue filtering with software filtering fully implemented in the MATLAB development environment. This method enables real-time processing of photodiode data, bypassing the limitations inherent in fixed analogue filtering. By exploiting the advantages of both approaches – hardware robustness and software flexibility – our hybrid system aims to improve PPG signal quality, thereby reducing artefacts associated with motion and ambient noise. The results of this research open up new prospects for the development of intelligent, reliable wearable devices for continuous health monitoring in a variety of clinical and ambulatory settings [7, 9, 13].

Photoplethysmography is a non-invasive technique used to measure physiological parameters like heart rate and blood oxygen saturation. The Pulse sensor is popular for this purpose due to its ability to detect light absorption variations. However, PPG signals are often affected by motion artefacts and ambient noise, compromising their accuracy. This research aims to explore the effectiveness of a hybrid filtering approach, combining analogue and software filtering and using the Pulse sensor. Which improve the accuracy of PPG signal extraction and open new perspectives for developing intelligent and reliable wearable devices for continuous health monitoring.

1. System design

1.1. Photoplethysmography signal

The photoplethysmography sensor, a cornerstone of the system, enables non-invasive heart rate measurement by capturing blood volume changes in peripheral tissues. The signal acquisition process begins with a green LED (520–550 nm wavelength) [1], selected for its optimal haemoglobin absorption properties, emitting light into the tissue. Reflected or transmitted light is detected by an APDS-9008 photodetector, which generates a proportional electrical current. This current is first converted into a voltage signal via a trans-impedance amplifier TIA to facilitate post-processing [11]. To mitigate high-frequency noise, such as motion artefacts and ambient interference, a low-pass RC filter is applied, preserving the pulsatile AC component of the PPG signal. The filtered signal is then amplified using an MCP6001 operational amplifier to ensure compatibility with the analog-to-digital converter ADC, which digitizes the signal for subsequent analysis. Fig. 1 shows the general block diagram of the proposed photoplethysmography signal acquisition system.

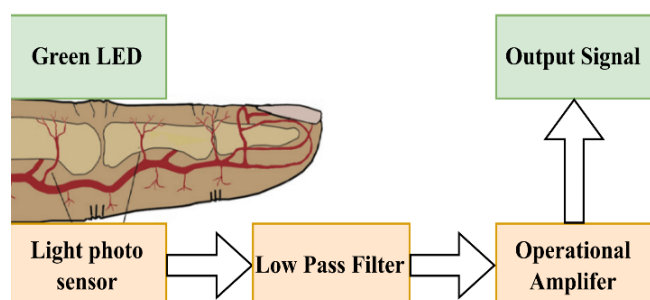


Fig. 1. General block diagram of a photoplethysmography

1.2. Green LED integration and signal processing in PPG systems

Green LEDs (500–550 nm) play a crucial role in the proposed photoplethysmography system due to their distinctive absorption properties suited for hemodynamic tracking. This wavelength range corresponds to strong absorption by both oxyhemoglobin (HbO₂) and deoxyhemoglobin (Hb), making green light particularly effective for high-contrast monitoring of microvascular dynamics, such as tissue perfusion and capillary refill studies [6, 12]. PPG systems typically pair LEDs with photodiodes (PDs) to detect the portion of light reflected from tissue that is not absorbed by blood. The amount of reflected light decreases as the concentration of absorbing chromophores increases. This interaction generates a pulsatile signal corresponding to the cardiac cycle: a lower signal (diastole) when blood volume is reduced, and a higher signal (systole) when blood volume increases [2]. To process the PPG signal, a low-pass filter is applied to suppress high-frequency noise, followed by amplification using an operational amplifier. The resulting waveform consists of two components: the alternating current (AC) component, representing pulsatile changes in blood volume, and the direct current (DC) component, reflecting baseline absorption due to constant tissue and blood volume. The basic optical measurement principle of the PPG signal is illustrated in Fig. 2a, while Fig. 2b shows the relationship between the AC and DC components, where the AC signal reflects heartbeats, and the DC component can be used to assess sympathetic nervous system activity, respiration, skin perfusion, and vascular tone [4, 10].

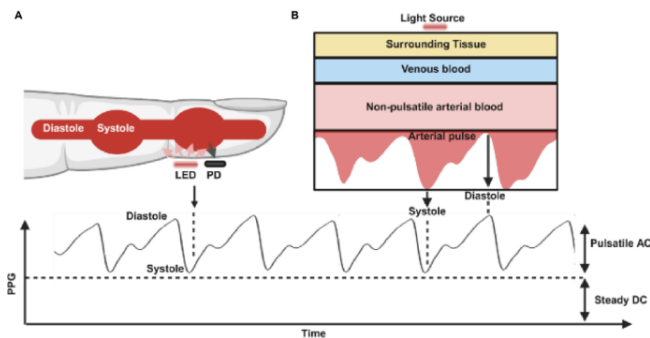


Fig. 2. The PPG principle states that light is transmitted differentially due to pulsatile blood flow in a vascularized target, like a fingertip, and absorption occurs during systole and diastole using reflectance mode. The AC to DC components of light transmission is crucial for determining blood oxygen saturation levels [4, 6]

2. Proposed model

Step 1: Connecting the heart rate sensor module to Arduino

Wiring connections

- The white cable connects the photodiode output to the Arduino A1 analogue input.
- The purple cable connects the sensor output to the Arduino A0 analogue input.
- The red cable is for the power supply (5V or 3.3V).
- The black cable connects to GND.

As shown in Fig. 3 after making this connection, the system is ready for compilation.

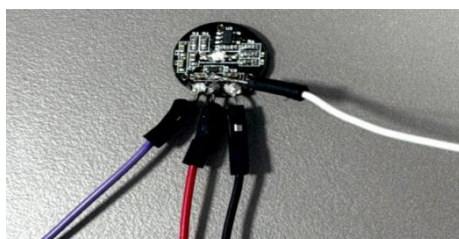


Fig. 3. Circuitry connection of the pulse-sensor

The pulse sensor system consists of a diode and a photodiode. When a finger is placed on the sensor, light from the diode causes disturbance due to blood flow variations. Blood absorbs some light from the diode, which is captured by the photodiode. The photodiode records these reflected beams, which vary with changes in blood flow caused by heartbeats. The detector outputs a DC signal, corresponding to blood volume and flow changes.

Step 2: Coding in Arduino (calculating heart pulse)

The primary objective of this code is to compare the performance of two different filtering methods on an analogue signal. The HARD filtering is achieved using external electronic components, while the SOFT filtering uses a moving average calculated by the Arduino microcontroller. This Arduino code illustrates a simple approach to comparing the performance of two analogue filtering methods. By using a moving average for software filtering, it allows for noise reduction in analogue signals while being easy to implement. This technique can be useful in various projects where signal quality is crucial.

3. Electronic schematic of photoplethysmography

This circuit uses a combination of optoelectronic and electronic components to detect and amplify a light signal. LED D1 emits light controlled by a resistor, while the APDS-9008 sensor converts the received light intensity into an electrical signal. A R2 pull-up resistor stabilizes its output. Low-pass filtering involves four capacitors and two resistors to eliminate spurious high frequencies, typical of RC stages. The MCP6001 operational amplifier boosts the signal with a gain determined by the negative feedback of R6 (3.3 MΩ), following a classic inverting amplification setup. Resistors R4-R5 bias the AOP in its linear range, while C5 decouples the power supply. The D2 diode protects against polarity reversal, and the whole assembly is supplied by VCC for stable operating voltage. Fig. 4 shows the complete electronic schematic of the proposed photoplethysmography circuit, including the LED, APDS-9008 sensor, RC filtering stages, MCP6001 amplifier, and Arduino interface. This arrangement finds applications in biomedical instrumentation and industrial optical control due to its ability to extract weak signals in noisy environments.

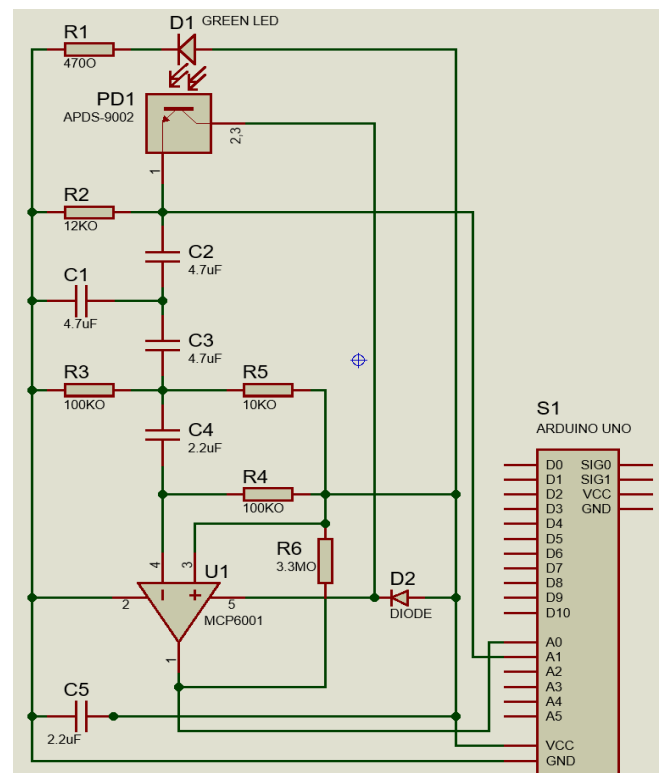


Fig. 4. Electronic schematic of a photoplethysmography by Proteus 8

Main equations for photoplethysmography (PPG) sensor components.

1. LED (Light Emitting Diode)

Current through the LED:

$$I_{LED} = \frac{V_{SUPPLY} - V_{LED}}{R_1} \quad (1)$$

where: I_{LED} – current through the LED, V_{supply} – supply voltage, V_{LED} – LED forward voltage, R_1 – series resistor to limit current

2. Light absorption by tissue (Beer-Lambert Law)

Transmitted light intensity:

$$I = I_0 \cdot e^{-\epsilon c l} \quad (2)$$

where: I – light intensity after passing through tissue, I_0 – incident light intensity, ϵ – molar extinction coefficient (depends on wavelength and blood oxygenation), c – concentration of absorber (haemoglobin), l – optical path length.

3. Photodetector (photodiode or phototransistor)

Photocurrent generated:

$$I_{PH} = S \cdot P \quad (3)$$

where: I_{ph} – photocurrent, S – sensitivity of the photodetector (A/W), P – incident optical power.

4. Low pass filter

Cut-off frequency:

$$f_c = \frac{1}{2\pi RC} \quad (4)$$

where: f_c – cut-off frequency (Hz), R, C – values of resistor and capacitor in the filter.

5. Operational amplifier

Non-inverting amplifier gain:

$$G = 1 + \frac{R_6}{R_5} \quad (5)$$

where: G – gain, R_6 – feedback resistor, R_5 – resistor between ground and inverting input

6. Heart rate calculation from PPG

Time domain method:

$$HR = \frac{60}{T} \quad (6)$$

where: HR – heart rate (bpm), T – time interval between two successive PPG peaks (seconds)

4. Results

The observed discrepancy between the hardware-filtered ("Hard", blue wave) and software-filtered ("Soft", red wave) heart rate values stems from processing delays inherent to the software algorithms. As shown in Fig. 5, the hardware-filtered and software-filtered heart rate signals exhibit a visible temporal offset, with the "Soft" waveform lagging behind the real-time "Hard" waveform. Techniques such as digital smoothing or moving averages analyse historical data points to compute outputs, introducing a lag termed group delay. This shifts the "Soft" values temporally ahead of the real-time "Hard" measurements. For example, when the "Hard" value is 68, the corresponding "Soft" value is not 60.77 (which reflects an earlier time point) but 70.39 in the subsequent measurement. Such misalignment creates inconsistencies in row-by-row comparisons, as the "Soft" data is offset by one or more sampling intervals. These temporal shifts can compromise real-time accuracy, especially in applications like exercise heart rate monitoring. To mitigate this, adjustments to temporal alignment (e.g., shifting "Soft" values backward), optimization of filter designs (e.g., linear-phase filters or reduced window sizes), and experimental calibration to quantify and correct latency are critical. Implementing these measures ensures synchronized data and reliable comparative analysis of both filtering methods.

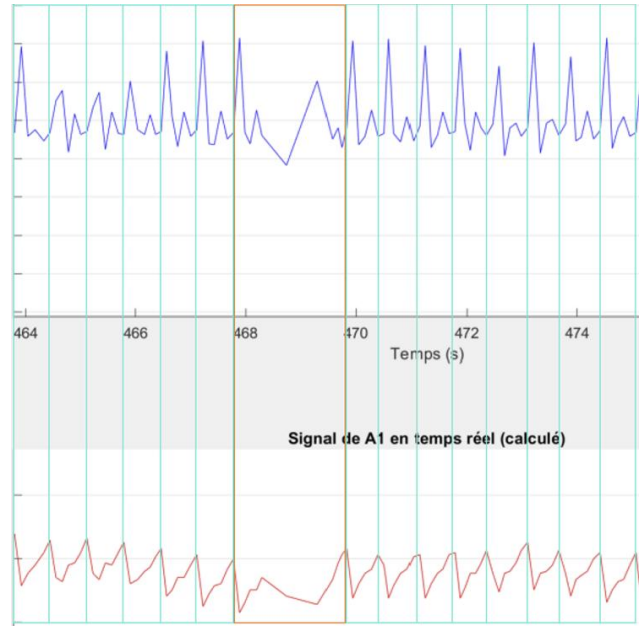


Fig. 5. Heart rate data comparison graph – blue for hard and red for soft by MATLAB

5. Discussion

This work presents a hybrid PPG signal filtering system combining analogue and digital techniques, exploiting the robustness of hardware RC low-pass filtering and the flexibility of software-based moving averages [14]. The use of a green LED (520–550 nm) enhances haemoglobin absorption contrast, optimizing hemodynamic monitoring, while the Arduino platform enables cost-effective implementation and adaptability to wearable devices [3]. However, critical limitations remain: a sampling rate of 10 Hz exposes the risk of spectral aliasing and neglects high-frequency artefacts [5], while moving averaging introduces a group delay of ~450 ms, putting signals out of sync [8]. The simplicity of this software method struggles to remove non-stationary noise (e.g. motion), and the lack of detailed analogue filter specifications (e.g. cut-off frequency) complicates latency analysis. In addition, the lack of quantitative validation (e.g. signal-to-noise ratio, heart rate error vs. ECG) weakens reliability claims. To overcome these constraints, future work will need to prioritize hardware optimization (e.g. low-noise op-amps, higher-order active filters) and software optimization (e.g. LMS-type adaptive algorithms, linear-phase FIR/IIR filters), coupled with an increase in sampling rate (≥ 50 Hz) to capture dynamic artefacts [5]. Rigorous validation via clinical references (ECG, SpO₂) and objective metrics (RMSE, Bland-Altman analysis) is essential to quantify performance gains. Multimodal integration (accelerometers, gyroscopes) could cancel out motion artefacts in ambulatory settings, while low-power embedded computing architectures would enable real-time processing on portable devices. Finally, targeted clinical trials (sportsmen and women, elderly patients, low perfusion environments) would validate the system's robustness and guide its evolution towards intelligent, precise health monitoring solutions adapted to the challenges of mobile care.

6. Conclusion

This study presents a hybrid filtering approach for PPG signals that synergizes analogue hardware robustness with digital software flexibility, demonstrating improved signal quality and noise resilience in physiological monitoring. By integrating a low-pass RC filter for baseline stabilization and a moving-average algorithm for real-time noise suppression, the system

effectively addresses motion artefacts and ambient interference, leveraging the Arduino platform's accessibility for scalable implementation. However, limitations like temporal misalignment due to software-induced delays, suboptimal sampling rates, and a lack of rigorous clinical validation underscore the need for further refinement. Future advancements should prioritize higher sampling rates, adaptive filtering techniques, and latency compensation to enhance real-time accuracy alongside comprehensive validation against clinical standards. Which ensure reliability in dynamic and real-world scenarios. These improvements could position hybrid PPG systems as cornerstone technologies for next-generation wearable devices, enabling precise, continuous health monitoring in diverse clinical and ambulatory settings.

References

- [1] Allen, J. (2007). Photoplethysmography and its application in clinical physiological measurement. *Physiological Measurement*, 28(3), R1–R39. <https://doi.org/10.1088/0967-3334/28/3/R01>
- [2] Biga, L. M., Dawson, S., Harwell, A., Hopkins, R., Kaufmann, J., LeMaster, M., Matern, P., Morrison-Graham, K., Quick, D., & Runyeon, J. (2019). 19.3 Cardiac cycle. In *Anatomy & Physiology*. OpenStax/Oregon State University. <https://open.oregonstate.edu/education/anatomy/chapter/cardiac-cycle/>
- [3] Camm, J., Klein, H., & Nisam, S. (2007). The cost of implantable defibrillators: Perceptions and reality. *European Heart Journal*, 28(4), 392–397. <https://doi.org/10.1093/eurheartj/ehl166>
- [4] Castaneda, D., Esparza, A., Ghamari, M., Soltanpur, C., & Nazeran, H. (2018). A review on wearable photoplethysmography sensors and their potential future applications in health care. *International Journal of Biosensors & Bioelectronics*, 4(4). <https://doi.org/10.15406/ijbsbe.2018.04.00125>
- [5] Fernández-Corazza, M., Beltrachini, L., Von Ellenrieder, N., & Muravchik, C. H. (2013). Analysis of parametric estimation of head tissue conductivities using Electrical Impedance Tomography. *Biomedical Signal Processing and Control*, 8(6), 830–837. <https://doi.org/10.1016/j.bspc.2013.08.003>
- [6] Franklin, D., Tzavelis, A., Lee, J. Y., Chung, H. U., Trueb, J., Arafa, H., Kwak, S. S., Huang, I., Liu, Y., Rathod, M., Wu, J., Liu, H., Wu, C., Pandit, J. A., Ahmad, F. S., McCarthy, P. M., & Rogers, J. A. (2023). Synchronized wearables for the detection of haemodynamic states via electrocardiography and multispectral photoplethysmography. *Nature Biomedical Engineering*, 7(10), 1229–1241. <https://doi.org/10.1038/s41551-023-01098-y>
- [7] Longmore, S. K., Lui, G. Y., Naik, G., Breen, P. P., Jalaludin, B., & Gargiulo, G. D. (2019). A Comparison of Reflective Photoplethysmography for Detection of Heart Rate, Blood Oxygen Saturation, and Respiration Rate at Various Anatomical Locations. *Sensors*, 19(8), 1874. <https://doi.org/10.3390/s19081874>
- [8] Orphanidou, C., Bonnici, T., Charlton, P., Clifton, D., Vallance, D., & Tarassenko, L. (2014). Signal Quality Indices for the Electrocardiogram and Photoplethysmogram: Derivation and Applications to Wireless Monitoring. *IEEE Journal of Biomedical and Health Informatics*, 1–1. <https://doi.org/10.1109/JBHI.2014.2338351>
- [9] Pizada, P., Wilde, A., & Harris-Birtill, D. (2024). Remote Photoplethysmography for Heart Rate and Blood Oxygenation Measurement: A Review. *IEEE Sensors Journal*, 24(15), 23436–23453. <https://doi.org/10.1109/JSEN.2024.3405414>
- [10] Tamura, T., & Maeda, Y. (2018). Photoplethysmogram. In T. Tamura & W. Chen (Eds), *Seamless Healthcare Monitoring* (pp. 159–192). Springer International Publishing. https://doi.org/10.1007/978-3-319-69362-0_6
- [11] Tamura, T., Maeda, Y., Sekine, M., & Yoshida, M. (2014). Wearable Photoplethysmographic Sensors—Past and Present. *Electronics*, 3(2), 282–302. <https://doi.org/10.3390/electronics3020282>
- [12] Teixeira, L., Ritti-Dias, R. M., Tinucci, T., Mion Júnior, D., & Forjaz, C. L. D. M. (2011). Post-concurrent exercise hemodynamics and cardiac autonomic modulation. *European Journal of Applied Physiology*, 111(9), 2069–2078. <https://doi.org/10.1007/s00421-010-1811-1>
- [13] Vijgeboom, T., Muller, M., Ebrahimkheil, K., Van Eijck, C., & Ronner, E. (2024). Evaluation of photoplethysmography-based monitoring of pulse rate, interbeat-intervals, and oxygen saturation during high-intensity interval training. *BioMedical Engineering OnLine*, 23(1), 114. <https://doi.org/10.1186/s12938-024-01309-w>
- [14] Zeitler, E. P., & Kramer, D. B. (2021). What Should Cardiac Patients Know About Device Cybersecurity Prior to Implantation? *AMA Journal of Ethics*, 23(9), E705-711. <https://doi.org/10.1001/amajethics.2021.705>

M.Sc. Hicham Loumissi

e-mail: hicham.loumissi-etu@etu.univh2c.ma

Ph.D. student in Industrial Engineering, Data Processing and Logistic Laboratory, University Hassan II, Faculty of Sciences, Casablanca, Morocco. His main research interests are biomedical signal processing, wearable health monitoring, embedded systems, and artificial intelligence for healthcare applications.



<https://orcid.org/0009-0003-8217-5196>

Prof. Adil Barra

e-mail: barra.adil@gmail.com

Professor in Physics Department at Faculty of Sciences, Hassan II University, Casablanca, Morocco. He is responsible of logistics engineering master degree and the electronics, electrical, automatic and industrial computing master degree. His main research interests are modelling logistic systems, electronics, automatic and industrial computing.



<https://orcid.org/0000-0002-5236-8857>

Prof. Najat Messaoudi

e-mail: najat.m2013@gmail.com

Professor in Physics Department at Faculty of Sciences, Hassan II University, Casablanca, Morocco. She is responsible of logistics engineering master degree and the electronics, electrical, automatic and industrial computing master degree. Her main research interests are modeling logistic systems, electronics, automatic and industrial computing.



<https://orcid.org/0000-0003-0041-9234>

Ph.D. Othmane El Badlaoui

e-mail: othmane-badlaoui@um5s.net.ma

Ph.D. in electrical engineering and information technology – Ensam-Ensias, Mohammed V University, Rabat – Morocco. Research Director at Suptech Essaouira. His main research interests are electrical engineering, embedded systems, artificial intelligence, and smart sensing technologies.



<https://orcid.org/0000-0002-9503-4398>

Ph.D. Hicham Medroumi

e-mail: h.medromi@yahoo.fr

Ph.D. Research Director at Hassan II University of Casablanca. His main research interests are industrial engineering, smart systems, digital transformation, and applied artificial intelligence.



<https://orcid.org/0000-0002-1132-978X>

Prof. Bahloul Bensassi

e-mail: bahloul.bensassi@yahoo.fr

Professor in Physics Department at Faculty of Sciences, Hassan II University, Casablanca, Morocco. He is responsible of logistics engineering master degree and the electronics, electrical, automatic and industrial computing master degree. His main research interests are modeling logistic systems, electronics, automatic and industrial computing.



<https://orcid.org/0000-0003-4129-4247>