A Low-cost Embedded Imaging System for Low-limb Vascular Metrics Monitoring

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***Abstract*—Cardiovascular metrics measurement and monitoring have been a critical need worldwide. The main objective of this work is to prototype an embedded imager for cardiovascular metrics monitoring. Utilizing an 850 nm Near-Infrared (NIR) light source and an Infrared (IR) camera, the system leverages the optical properties of human skin to extract Photoplethysmogram (PPG) signals, heart rate, and vascular structure from video data. We tested the system with 10 participants, comparing its heart rate measurements to those obtained from a contact PPG sensor, achieving an accuracy within ±5 bpm. Additionally, using an artificial hand phantom for blood vessel visualization, the system demonstrated a vessel extraction accuracy with an average error of 10.21% in blood vessel width, confirming the effectiveness of our NIR-enhanced imaging approach.**

***Index Terms*—Embedded Systems; Vascular Biometrics; Blood flow and Vessel; Wound healing.**

I. Introduction

Peripheral arterial disease (PAD) is a prevalent cardiovascular condition, affecting an estimated 8-12 million Americans, with a higher incidence in the elderly and diabetic demographics [1]. PAD is a major health concern, increasing the risk of heart attack, stroke, and death. Continuous monitoring of cardiovascular indicators, such as pulse rate, blood pressure, and electrocardiograms (ECGs), are crucial for early intervention and treatment. Clinical settings now use a variety of sensors for accurate measurements. To enhance portability and affordability, researchers are actively developing medical imaging algorithms. These advancements offer new opportunities to create compact, reliable, and cost-effective solutions for cardiovascular monitoring, meeting the growing demand among healthcare professionals.

Current methods for diagnosing Peripheral Artery Disease (PAD) are constrained by the capabilities of existing devices. The Ankle-Brachial Index [2] is a simple and common diagnostic method, but it can be unreliable due to variability in healthcare provider proficiency, especially in diabetic patients. Additionally, advanced diagnostic techniques such as Computed Tomography Angiography and Magnetic Resonance Angiography pose risks to patients with renal insufficiency, a common condition among PAD patients [3]. These limitations significantly hinder effective PAD diagnosis and treatment. Furthermore, these diagnostic devices often impose high costs on patients, making them inaccessible to many, particularly those in underfunded healthcare systems or low-income regions. The large size of these devices also presents challenges, making them difficult to deploy in small clinics and remote areas with limited space and resources. These factors collectively impede the widespread and effective diagnosis and treatment of PAD. Therefore, an affordable, compact, and advanced biomedical sensing system is urgently needed to improve cardiovascular health monitoring and PAD management. Such a system would enhance accessibility, allowing for more equitable healthcare delivery and facilitating the early detection and treatment of PAD in a variety of clinical settings.

Vascular structure and PPG measurements, including pulsation strength, heart rate (HR), and heart rate variability (HRV), are essential for diagnosing PAD. Vascular imaging identifies blockages and assesses arterial damage, while PPG provides information about blood flow and circulation quality. Weak or irregular PPG signals indicate poor blood flow, common in PAD patients. Combining these techniques enhances early detection, non-invasive monitoring, and comprehensive vascular assessment, improving PAD management and patient outcomes [4].

Therefore, we propose developing an embedded imager for vascular imaging and PPG extraction. Leveraging the optical properties of human skin, we integrated a low-cost Near-Infrared (NIR) light source, IR camera, and Jetson Nano to capture real-time skin video signals. After noise filtering, we apply signal processing to extract PPG signals, heart rate, and vascular patterns. We validated the system with 10 participants using contact PPG sensors and assessed vein imaging accuracy with an artificial hand phantom. This approach ensures reliable and effective cardiovascular data collection.

II. Methods

A. Hardware Design and Implementation

The designed embedded system for cardiovascular monitoring, as illustrated in Figure 1, employs near-infrared (NIR) light and an infrared camera to capture skin video, enhancing the visualization of vascular structures due to the optical properties of hemoglobin and vessel walls. This setup, shown in Figure 2, includes an IMX219-77IR camera connected to an Nvidia Jetson Nano, optimizing the contrast of subcutaneous blood vessels for clearer imaging. The system architecture supports simultaneous extraction and analysis of heart rate and vascular structure via a noise reduction module that ensures data accuracy and a GUI that visually represents

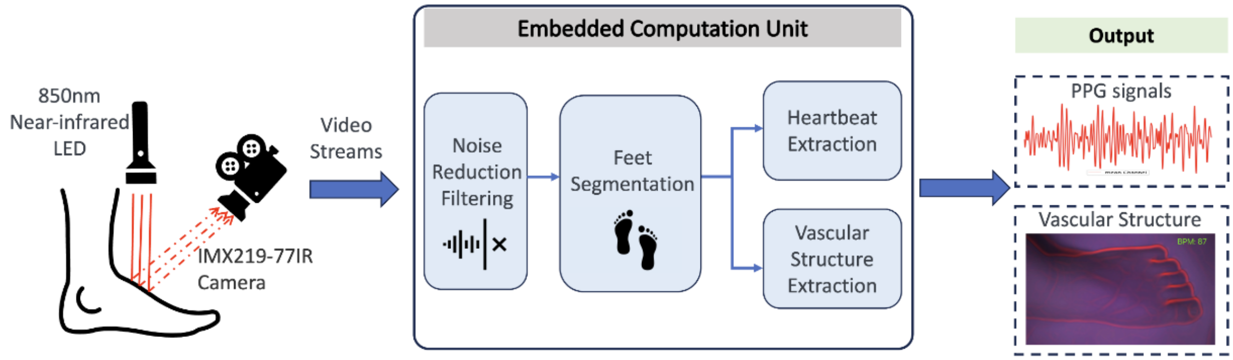


Fig. 1. System diagram. The optical hardware consists of a near-infrared light sensor and an infrared camera, which is used to record skin video. The recorded video streams are then fed to an embedded computation unit for extracting PPG signals and vascular structure.

the cardiovascular data. Among the key design challenges were integrating NIR technology to enhance visibility of subcutaneous vessels, balancing the sensitivity of the camera with the processing power of the Jetson Nano for efficient real-time image processing, and creating a user interface that is intuitive and facilitates easy analysis of the cardiovascular metrics. By overcoming these challenges, the system effectively combines advanced imaging techniques and efficient processing hardware to deliver a comprehensive solution for real-time cardiovascular monitoring.

B. Heart Rate Extraction

Resting heart rate is a vital health metric, indicative of overall and cardiovascular health, and is crucial for predicting all-cause and cardiovascular mortality [5].

Our method uses a NIR light and an IR camera system, selected for their sensitivity to oxyhemoglobin, which reflects red light and absorbs infrared light, unlike deoxyhemoglobin. Heart rate is measured using a PPG system to record the light signal's AC and DC components [6]. The AC component reflects heartbeat-induced blood flow variations, while the DC component provides a baseline. The PPG signal's periodicity indicates heart-driven blood volume fluctuations, essential for accurate heart rate assessment. By analyzing the AC component, we measure heart rate precisely. The systolic peak is isolated as a one-dimensional discrete signal, m[n], with n as the discrete time index. The peak detection process is formulated as:

$$P=\{n\,|\,m[n]>m[n-i] \text{ and } m[n]>m[n+i],\, \forall i, 1\leq i\leq D\}\,, \quad \text{where } D=\text{int}(0.3\times \text{fps}). \tag{1}$$

Here, D is set to 0.3 times the frame rate per second (fps), limiting heart rate detection to under 200 bpm. This balances sensitivity and specificity in peak detection, reflecting the typical heart rate range. After peak extraction, the frequency is confined to 0.8-2 Hz using band-pass filtering, aligning with resting heart rates and reducing noise. Verified heart rate peaks allow heart rate calculation based on the average time interval between successive peaks, defined as:

Consider P = p1, p2, …, pk denote the set of indices corresponding to the verified heart rate peaks, the heart rate is calculated based on the average time interval between these successive peaks. The heart rate computation can be mathematically defined as :

$$\begin{aligned} HR&=\frac{60}{T}, \\ \text{where } T&=\frac{1}{k-1}\sum_{i=1}^{k-1}\left(\frac{p_{i+1}-p_i}{\text{fps}}\right). \end{aligned} \tag{2}$$

C. Vascular Structure Extraction

Vascular imaging is crucial for diagnosing and treating cardiovascular diseases. Our system includes a vascular structure extraction module to improve cardiovascular health assessment. Near-infrared light (NIR) is effective in vascular imaging due to its absorption by hemoglobin. Human veins, located 1-3 mm beneath the dermis [7], [8], are visualized effectively using NIR light, which penetrates tissue with less absorption and scattering than visible light [9]. NIR wavelengths of 850-900 nm enhance contrast between skin and vessels, providing clearer images. Effective noise reduction, using histogram equalization and Gaussian noise filters, is essential for extracting blood vessels. The SATO filter, used for vessel detection, enhances tubular structures in images by analyzing the local structure through multi-scale line detection. This process involves calculating the eigenvalues and eigenvectors of the Hessian matrix at each pixel across multiple scales. The SATO Linear filter is expressed by the following equation:

$$\lambda_{12}=\begin{cases} |\lambda_2|\left(\frac{|\lambda_1|}{|\lambda_2|}\right)^{\gamma_{12}}\left(1+\frac{|\lambda_1|}{|\lambda_2|}\right)^{\gamma_{12}}, & \text{if } \lambda_2<\lambda_1\leq 0 \\ |\lambda_2|\left(\frac{|\lambda_1|}{|\lambda_2|}\right)^{\gamma_{12}}\left(1-\alpha\frac{|\lambda_1|}{|\lambda_2|}\right)^{\gamma_{12}}, & \text{if } \lambda_2<0<\lambda_1<\frac{|\lambda_2|}{\alpha} \\ 0. & \text{otherwise} \end{cases} \tag{3}$$

This formulation ensures effective enhancement of both tubular and spherical structures, characteristic of blood vessels.

III. Results and Discussion

A. PPG Response to Heart Rate

We recorded PPG signals for ten participants using both a contact PPG sensor and our non-contact system. Participants

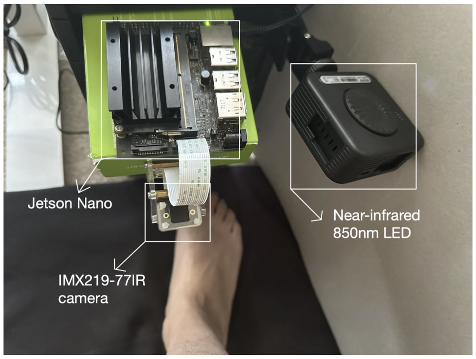


Fig. 2. Hardware Setup using an IR camera and a 850 nm NIR LED.

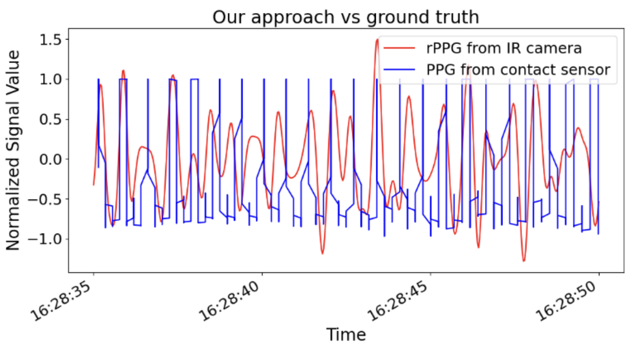


Fig. 3. PPG signals comparison: baseline PPG collected by contact sensor (blue) vs. PPG extracted from our system (red). The results show high correlation between baseline and our system measurements.

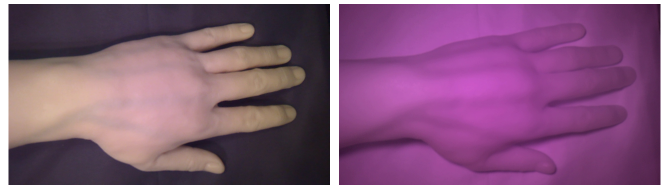
attached the contact sensor to their fingers, and these signals were timestamped as the ground truth. Despite differences in amplitude and waveform shape due to sensing methods, peak frequencies were similar. Table I shows heart rates from both systems, with error rates mostly within ±5 bpm. Contact sensors provide stable measurements, while non-contact systems must account for factors like ambient light and distance. However, non-contact systems enhance convenience and comfort by eliminating direct contact, which minimizes patient disturbance or when contact measurements are impractical.

Further development of non-contact PPG technology could improve its accuracy and reliability, making it a viable alternative to traditional contact-based systems. Future research will focus on optimizing signal processing algorithms to enhance non-contact PPG signal quality and minimize discrepancies with ground truth data.

TABLE I
COMPARISON OF HEART RATE MEASUREMENTS: CONTACT SENSOR VS. OUR SYSTEM

Subject	Our system (BPM)	Contact sensor (BPM)	error (BPM)
1	80.71	73.00	-7.71
2	76.67	71.46	-5.21
3	102.4	100.6	-1.8
4	86.75	89.16	2.41
5	84.46	87.72	3.26
6	87.80	85.86	-1.94
7	108.65	105.96	-2.69
8	94.88	90.24	-4.64
9	88.34	92.40	4.06
10	72.25	71.00	-1.25

B. Detection of Vascular Structure



(a) Hand phantom under Normal light (b) Hand phantom under NIR light

Fig. 4. Hand phantom image quality comparison between (a) under normal light, and (b) under NIR light. Imaging under NIR light shows stronger contrast in vessel visualization.

TABLE II
QUANTITATIVE COMPARISON OF BLOOD VESSEL WIDTH MEASUREMENTS: MANUAL CALIBRATION MEASURED ORIGINALS VS. ALGORITHMICALLY DETECTED VALUES

Vessel location	Original Width	Detected Width	Error (%)
1	28	27	3.5%
2	34	30	11.7%
3	50	57	14.0%
4	35	30	16.6%
5	30	29	3.3%
6	43	39	9.3%
7	35	35	0.0%
8	46	38	17.3%
9	31	33	6.4%
10	45	36	20%
		Average Error:	10.21%

Our study leverages artificial blood vessel hand models, which mimic human tissue properties, to improve vascular imaging. These phantoms allow for precise evaluations of imaging techniques. Artificial silicon, used as a skin substitute, effectively simulates light penetration through human-like tissues [10], providing a realistic platform for testing our methods. The consistent and controllable nature of these models ensures reliable assessments of vascular structure extraction, serving as an effective benchmark for image accuracy.

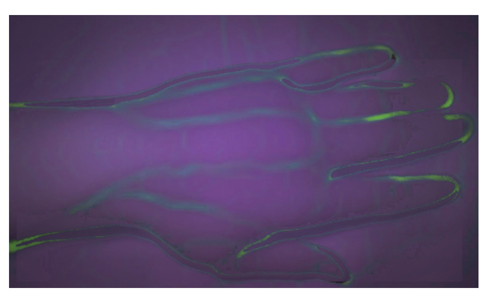
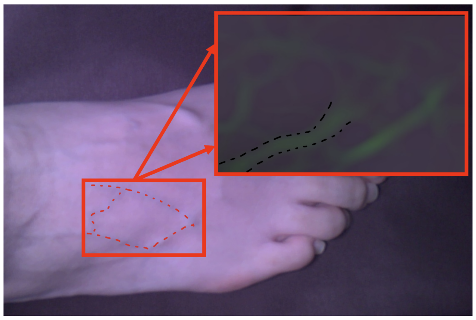


Fig. 5. Extracted vessel is overlapped on the image frame (Green line indicates extracted vessel).



(a) Enlarged view of the vessel pattern extracted from a subject's foot under Normal light

(b) Enlarged view of the vessel pattern detected from a subject's foot under NIR light

Fig. 6. Comparative analysis of vessel patterns extracted from a subject's foot (a) under normal light, and (b) under NIR light. The red dashed line delineates the actual vascular structure, while the black dashed line indicates the erroneously generated vessels by the algorithm under normal lighting. NIR lighting significantly enhances the algorithm's precision in delineating accurate and clear vascular structures.

Under NIR light, blood vessels stand out clearly against surrounding material Figure 4(b) , much more distinctly than under normal light Figure 4(a). NIR illumination, combined with SATO filters, greatly enhances vascular structure visualization Figure 5. Overlaid images accurately depict the hand phantom's vascular network, demonstrating the effectiveness of NIR imaging and SATO filters. Tests on subjects' feet further confirmed this. Figure 6(a) shows vessel patterns under normal light, with some inaccuracies marked by black dashed lines. In contrast, Figure 6(b) highlights NIR lighting's ability to accurately delineate vascular structures, reducing false positives. This comparison underscores NIR lighting's superiority in providing clearer and more accurate blood vessel images.

To evaluate our vascular imaging method's accuracy, we conducted a manual calibration test. We selected 10 random blood vessel locations from a hand phantom and measured their widths using a bitmap image editor. These measurements were compared to those obtained by our imaging system. Table II shows the original and detected widths, along with the error percentages. The average width estimation error was 10.21

IV. Conclusion

A non-contact embedded imager for monitoring heart rate and vascular structure was developed. The system uses an IMX-219 IR camera to capture video signals from the skin, obtaining PPG and vessel signals. The IR camera and NIR light improve light penetration in human tissue, achieving an error of ±5 bpm in heart rate extraction. A hand phantom with preset vascular structures was used to evaluate blood vessel extraction accuracy. The system successfully detected all preset structures, with an average discrepancy of 10.21% in vessel width measurement.

The embedded system can continuously assess heart rate and blood vessels to detect potential wounds and diseases related to abnormal blood flow. Future work will focus on improving heart rate accuracy by refining PPG extraction methods and reducing dependence on light stability. Additionally, optimizing the packaging of IR cameras and NIR light will enhance the system's portability and user-friendliness.

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