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Proceeding Paper

Mechatronic System Design of a Low-Cost Near-Infrared Vein Visualization Platform Based on Optoelectronic Integration †

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Abstract

Near-infrared (NIR) imaging systems have demonstrated significant potential for enhancing subcutaneous visualization applications; however, existing solutions are typically based on proprietary architectures with limited accessibility for experimental and engineering development. This work presents the mechanical and mechatronic design of a low-cost NIR vein visualization platform focused on optoelectronic integration, structural stability, and real-time image acquisition performance. The proposed system combines a controlled NIR illumination module, an infrared-sensitive imaging unit, and a compact processing architecture designed to operate under constrained computational resources while maintaining consistent visualization conditions. The mechanical structure was developed to ensure fixed spatial alignment between illumination and sensing components, minimizing optical noise and shadow artifacts through controlled geometry and working distance optimization. Image processing routines based on grayscale conversion and contrast enhancement were implemented to improve signal differentiation between vascular and surrounding tissue structures while preserving real-time operation capability. The modular architecture enables rapid prototyping, component scalability, and reproducibility using commercially available hardware elements. Experimental functional evaluation demonstrated stable visualization of superficial vascular patterns under controlled conditions, confirming adequate optical response and system repeatability for continuous operation scenarios. Compared with commercially available systems, the proposed platform significantly reduces implementation cost while preserving essential functional performance required for optoelectronic sensing applications. The presented design highlights the potential of low-cost mechatronic integration for developing scalable optical sensing platforms, providing a foundation for future improvements involving automated calibration, advanced image processing, and adaptive control strategies in electromechatronic systems.

Keywords: near-infrared imaging; mechatronic integration; vein visualization; low-cost sensing systems; image processing

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1. Introduction

Peripheral venous access is recognized as one of the most fundamental and frequently performed invasive procedures in clinical medicine, with estimates suggesting that 90% to 95% of hospitalized patients require intravenous (IV) administration for medications, fluids, or blood sampling [1,2]. Despite its routine nature, the procedure is fraught with challenges, primarily due to the clinical condition known as Difficult Venous Access (DVA). DVA affects between 10% and 26% of general hospitalized populations and can reach up to 60% in high-risk groups, such as pediatric, geriatric, and obese patients [3,4]. This condition arises when superficial veins are neither easily palpable nor visible due to physiological factors like skin tone, subcutaneous fat distribution, or dehydration [4,5].

The importance of improving venous localization technology lies in the multidimensional impact of failed attempts. Clinically, multiple punctures increase the risk of hematomas, infections, nerve injury, and "vascular exhaustion," where no viable sites remain for puncture [5,6]. From an economic perspective, DVA management represents a substantial burden, with estimated annual costs of $4.7 billion in the United States due to delayed diagnostics and extended hospital stays [3]. Therefore, transitioning from traditional palpation to technology-assisted "visualized localization" is essential to improve first-attempt success rates and enhance patient safety [7].

Near-Infrared (NIR) technology is the most effective non-invasive method for subcutaneous vascular visualization [8]. The biophysical principle is based on the fact that deoxygenated hemoglobin in venous blood has a significantly higher light absorption coefficient in the NIR spectrum (typically between 740 nm and 960 nm) compared to surrounding tissues [5,9]. Consequently, under NIR illumination, veins appear as dark patterns against a lighter background of skin and fat [1,9].

Recent research has focused on developing low-cost prototypes utilizing off-the-shelf components. Studies have demonstrated the viability of using Raspberry Pi (OS Trixie) microprocessors, CMOS sensors without IR filters, and NIR-LED arrays to capture real-time vascular images [4,10]. Regarding optical parameters, a wavelength of 850 nm is frequently cited as optimal due to its balanced penetration depth (up to 5 mm) and high contrast ratio [5,10]. In terms of software, image processing algorithms such as Contrast Limited Adaptive Histogram Equalization (CLAHE) and Wiener filters are standard for reducing optical noise and enhancing the visibility of the vein network [8,9]. From an educational technology standpoint, these devices serve as critical instructional tools. Studies confirm that vein viewers contribute immensely to the improvement of their practical skills in nursing students, significantly reducing site selection time and increasing clinical confidence [1,5].

Despite the potential of NIR imaging, significant gaps remain in the current field. A primary barrier is the high cost of commercially available devices, which range from $4500 to $27,000, limiting their accessibility in resource-constrained educational and clinical settings [1,5]. Furthermore, existing solutions are often built on "proprietary architectures with limited accessibility" for experimental development and iterative engineering improvements. Technical limitations also include susceptibility to optical noise, shadow artifacts, and the loss of real background color information during image fusion [11]. The proposed platform focuses on fixed optical alignment, controlled geometry, and working distance optimization using commercially available hardware.

The present article details the mechanical and mechatronic design of a low-cost NIR vein visualization platform. The primary objective is to develop a system that integrates a controlled NIR illumination module with an infrared-sensitive imaging unit and a compact processing architecture capable of real-time performance even under constrained computational resources. The justification for this design lies in its ability to significantly reduce

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implementation cost while preserving essential functional performance required for clinical and educational applications. The main scientific contributions of this work are threefold. First, a low-cost mechatronic platform for near-infrared vascular visualization was developed using commercially available hardware and technologies. Second, an optoelectronic architecture integrating concentric NIR illumination, infrared image acquisition, and embedded real-time processing was designed to improve the visualization of superficial vascular structures. Finally, the proposed system was experimentally validated using an anatomical vascular phantom, demonstrating the feasibility of the proposed architecture for educational, biomedical engineering, and rapid prototyping applications.

2. System Design and Methods

2.1. Overall Mechatronic Architecture

The proposed platform was developed as a compact, low-cost mechatronic system for near-infrared (NIR) vein visualization. The system integrates four main subsystems: (i) an NIR illumination module, (ii) an infrared-sensitive CMOS camera, (iii) an embedded processing unit, and (iv) a mechanical support structure. The illumination module projects NIR light onto the target, while the camera captures the reflected radiation to reveal vascular structures based on the absorption properties of hemoglobin. The embedded processor performs real-time image enhancement, and the mechanical structure maintains stable alignment between the optical components. Figure 1 shows the proposed system architecture and the developed prototype, showing how the NIR illumination, image acquisition, and processing components are integrated to obtain and display vein-related image information.

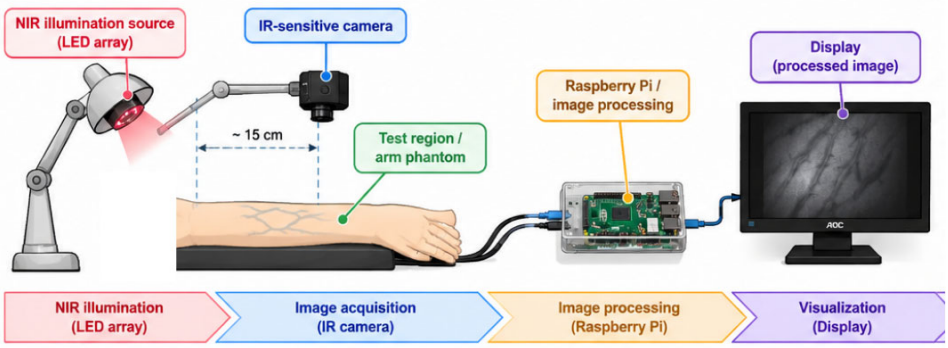


Figure 1. Mechatronic architecture and experimental prototype of the proposed NIR vein visualization platform.

2.2. Optoelectronic and Mechanical Integration

The optoelectronic subsystem combines a circular array of NIR LEDs operating in the 740–850 nm wavelength range with an infrared-sensitive CMOS camera. The concentric LED arrangement provides uniform illumination while reducing shadows and reflections during image acquisition. The camera operates without the conventional IR-cut filter to enable detection of reflected NIR radiation from the vascular phantom. No additional long-pass or band-pass optical filter was used in the current prototype; therefore, ambient visible light may contribute to the acquired signal. Controlled and constant laboratory illumination was used to minimize variations in this contribution. The imaging module is mounted on an articulated mechanical support that allows adjustment of the working distance and viewing angle while maintaining stable optical alignment. The modular structure reduces motion artifacts and facilitates future hardware upgrades using commercially available components. The 740–850 nm emission range corresponds to the spectral bandwidth of the selected commercial NIR LED array chosen to approximate the 850 nm absorption

optimum reported in the literature [5,10] while remaining within the cost and availability constraints of commercially available low-cost components.

2.3. Image Processing Pipeline

Infrared images were acquired in grayscale and processed in real time using lightweight computer vision algorithms implemented on a Raspberry Pi embedded platform. The processing sequence consisted of Gaussian filtering for noise reduction, CLAHE for local contrast enhancement, intensity normalization, and vessel enhancement to improve visualization of vascular patterns. The improved pipeline provided continuous real-time visualization while maintaining low computational requirements suitable for embedded systems. The processing pipeline was configured using a CLAHE clip limit of 2.0 with an 8×8 tile grid, Gaussian filtering with a 5×5 kernel and $\sigma = 1.0$, and intensity normalization based on the 1st and 99th percentile intensity values, followed by linear scaling to the [0, 255] range. These parameters were standardized to provide consistent image enhancement while maintaining the computational efficiency required for real-time embedded processing. The selected image-processing techniques were chosen because of their low computational complexity and suitability for embedded platforms with limited processing resources. This approach enables real-time execution while preserving sufficient image quality for vascular visualization without requiring dedicated graphics hardware.

2.4. Hardware Implementation

The prototype was assembled using low-cost, commercially available components to improve affordability and reproducibility. The hardware includes an NIR LED illumination module, an infrared-sensitive CMOS camera, a Raspberry Pi, a regulated power supply, and a 3D-printed mechanical housing. Compared with commercial vein visualization devices such as VeinViewer and AccuVein, the proposed platform substantially reduces implementation cost while preserving the essential functionality required for real-time vascular visualization. Its modular architecture also supports future integration of advanced image-processing algorithms and additional sensing technologies. Table 1 summarizes the main hardware components, their technical specifications, and their functional roles in the proposed system. This information clarifies the contribution of each component to system operation and supports the reproducibility of the prototype. Component costs may also be reported to substantiate the low-cost characterization of the proposed platform.

Table 1. Technical specifications of the proposed low-cost NIR vein visualization prototype.

Component	Specification	Function in the System	Cost (USD)
Embedded processor	Raspberry Pi 4 Model B	Image processing and system control	44
IR-sensitive camera	Infrared-sensitive CMOS, IR-cut filter removed; 640×480 px; 20–30 FPS	NIR image acquisition	98
NIR LED array	5 V DC, regulated	Illumination of the test region	7
Power supply	Work lamp, nickel-plated	Electrical power supply	6
Mechanical support/housing	Raspberry Pi 4 Model B	Component positioning and mechanical support	39

3. Experimental Setup

3.1. Experimental Configuration

The proposed near-infrared (NIR) visualization system was experimentally validated under controlled laboratory conditions to evaluate the performance of the optoelectronic platform and the embedded image-processing pipeline. A commercial anatomical training arm was used instead of human subjects to provide repeatable experimental conditions. The phantom consisted of a synthetic forearm containing transparent silicone tubes filled with artificial blood, simulating superficial blood vessels while eliminating physiological variability. The use of an anatomical training arm enabled controlled and repeatable experiments while avoiding the ethical and physiological variability associated with human subjects during the preliminary validation stage. This approach allowed objective evaluation of the optoelectronic configuration before future clinical testing.

The prototype employed an articulated desk lamp as the mechanical support for the optoelectronic module, allowing precise adjustment of the illumination angle and working distance. The acquisition head integrated a circular array of NIR LEDs operating within the 740–850 nm wavelength range around an infrared-sensitive CMOS camera. Image acquisition and processing were performed using a Raspberry Pi connected to an external monitor for real-time visualization. Ten independent experimental trials were conducted under identical operating conditions. During each trial, the phantom remained fixed while the imaging module was positioned between 10 and 20 cm from the target surface. Ambient illumination was maintained constant to minimize visible-light interference during infrared acquisition. Figure 2 shows the experimental testing setup, including the arrangement of the prototype and the main elements involved in image acquisition and evaluation.

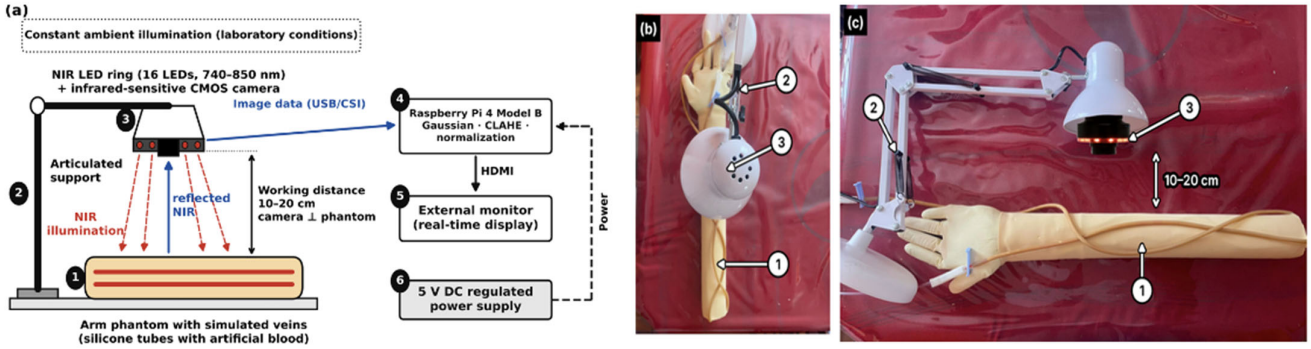


Figure 2. Experimental testing setup: (**a**) system configuration; (**b**) side view of the prototype; and (**c**) experimental arrangement showing the relative positioning of the NIR source and arm phantom.

3.2. Image Acquisition and Processing

Before each experiment, the optical system was calibrated by aligning the camera perpendicular to the phantom surface and manually adjusting the focus to maximize visualization of the blood-filled tubes. Camera exposure, gain, and acquisition parameters remained unchanged throughout all experiments. Images were acquired in grayscale at 20–30 frames per second, providing continuous real-time visualization with low computational requirements.

Approximately 300 consecutive frames were captured during each trial. Image processing was implemented in Python (3.14) using the OpenCV library (4.11). The processed images were displayed in real time with minimal latency. Figure 3 shows the experimental setup and the image-processing workflow.

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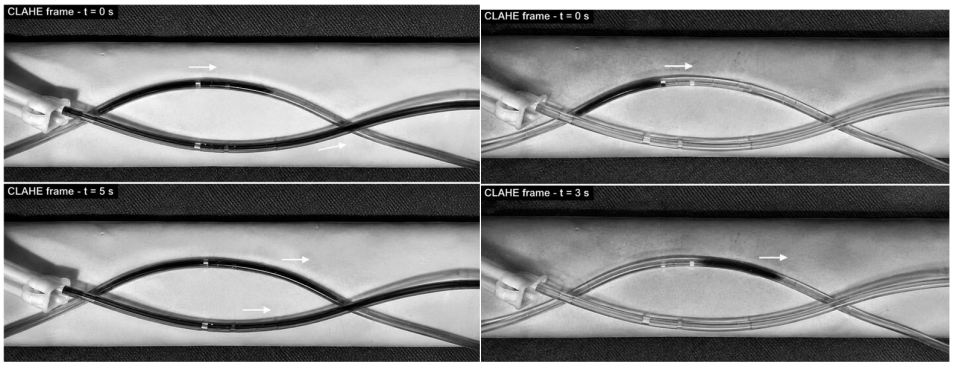


Figure 3. Representative CLAHE-processed grayscale NIR frames obtained during two experimental trials at different acquisition times. The arrow indicates the direction of blood flow.

3.3. Performance Evaluation

System performance was qualitatively evaluated by analyzing the enhanced visualization of the blood-filled tubes obtained during the ten experimental trials. Assessment focused on image contrast, visualization stability, suppression of illumination artifacts, repeatability under identical conditions, and mechanical stability of the support structure. Continuous operation tests of approximately 30 min demonstrated stable illumination, consistent image quality, and uninterrupted real-time processing. These results confirm the feasibility of the proposed low-cost mechatronic platform as an experimental tool for NIR vascular imaging and provide a foundation for future developments in automated vessel segmentation and embedded computer vision. Across the ten trials, the system exhibited visually consistent behavior under identical operating conditions, as judged qualitatively by the operators. No quantitative repeatability statistics (e.g., mean/SD of image-quality metrics across trials) were computed in the present study; this is identified as a limitation and a priority for future quantitative evaluation. In 7 of the 10 trials, visualization was qualitatively judged successful by the operators. Given the limited sample size (n = 10), this proportion is reported descriptively, and no confidence interval or inferential statistical claim is made. The attribution of failures to illumination angle sensitivity reflects qualitative observation recorded during the trials rather than systematic angle measurements or comparative imaging.

4. Results and Discussion

A total of ten experimental trials were completed under identical acquisition conditions, generating approximately 3000 infrared frames for qualitative analysis. Stable real-time operation was maintained throughout the ten experimental trials; however, successful visualization of the simulated vascular structures was qualitatively observed in 7 of the 10 trials. The proposed near-infrared (NIR) visualization system successfully detected the artificial blood circulating inside the silicone tubes of the anatomical training arm during the ten experimental trials. The combination of concentric NIR illumination and an infrared-sensitive CMOS camera generated sufficient optical contrast to distinguish the simulated vascular structures from the surrounding phantom material. The processed images exhibited improved visibility and continuity of the blood-filled tubes, demonstrating the effectiveness of the proposed low-cost optoelectronic configuration.

The implemented image-processing pipeline significantly enhanced image quality compared with the raw infrared acquisitions. Gaussian filtering reduced sensor noise, while CLAHE increased local contrast, allowing clearer differentiation of the artificial blood within the silicone tubes. Intensity normalization further improved visualization consistency under identical acquisition conditions. The complete processing sequence was

executed in real time at acquisition rates between 20 and 30 FPS, providing continuous visualization without perceptible latency. The selected 640 × 480 px resolution constrains the minimum vessel diameter that can be reliably resolved at the working distance of 10–20 cm, which may limit sensitivity to very thin superficial veins relative to higher-resolution commercial systems. Detection of deeper-lying veins is additionally constrained by the limited penetration depth of NIR illumination in the 740–850 nm range [5,10], rather than by camera resolution. The 20–30 FPS acquisition rate was selected to support real-time visualization under the computational constraints of the embedded platform and was not identified as a limiting factor for the quasi-static imaging conditions used in this study.

The mechanical configuration also contributed to system performance. The articulated support maintained stable alignment between the illumination module and the imaging sensor throughout the experiments, reducing optical artifacts caused by variations in distance or illumination angle. Continuous operation for approximately 30 min demonstrated stable illumination intensity and consistent image quality without noticeable degradation in processing performance.

Compared with commercial systems such as VeinViewer and AccuVein, the proposed platform uses commercially available components and a modular structure, reducing implementation costs while providing the essential functionality required for experimental NIR visualization.

Although the proposed platform demonstrated satisfactory performance during phantom-based validation, the present study was limited to controlled laboratory conditions and qualitative image assessment. Future work will include quantitative image quality metrics, evaluation with human subjects, and integration of artificial intelligence algorithms for automatic vessel segmentation and localization. Image quality in this work was evaluated qualitatively through visual inspection by the authors rather than through quantitative metrics such as Michelson contrast ratio, SNR, or CNR; this is identified as an important limitation, and quantitative characterization of image quality is planned for future work. The mechanical aspects of this work were validated functionally rather than through formal structural analysis. Finite element analysis, tolerance stack-up analysis, and vibration testing were not performed in the present study and are identified as necessary steps for a complete mechatronic characterization of the platform in future work.

5. Conclusions

This work presented the design and evaluation of a low-cost near-infrared (NIR) vein visualization platform based on mechatronic and optoelectronic integration. The system combined controlled NIR illumination, infrared-sensitive image acquisition, embedded real-time processing, and mechanically optimized alignment within a compact and modular architecture. Experimental results demonstrated stable visualization of superficial vascular structures under controlled conditions. Image enhancement techniques, including grayscale normalization and adaptive contrast enhancement, improved vascular differentiation while maintaining real-time operation under limited computational resources. The mechanical configuration reduced optical noise and shadow artifacts through fixed spatial alignment between illumination and sensing modules. Furthermore, the modular design enabled scalability and reproducibility using commercially accessible components. Compared with commercial vein visualization devices, the proposed platform achieved significant cost reduction while preserving essential visualization functionality for educational and experimental biomedical applications. Despite the satisfactory performance, several limitations were identified. The system was evaluated mainly under controlled indoor illumination, and its performance may decrease under variable environmental conditions. In addition, the current processing pipeline relies on lightweight algorithms and

does not include advanced segmentation or artificial intelligence techniques. Physiological differences among users, such as skin pigmentation and vascular depth, may also affect image quality. Overall, this work provides a scalable foundation for accessible NIR-based biomedical visualization systems.

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