Non-contact measurement of heart rate using red and near-infrared illumination

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Abstract. This thesis report presents a portable and low-cost system and methodology to image subsurface vasculature and measure heart rate using red and near-infrared illumination. This is achieved using image acquisition and processing focused on isolating the finger dimensions and measuring the width of the blood vessel. The variation of the blood vessel size is used to calculate the heart rate and, for validation, compare it with measurements from a standard pulse oximeter. Unlike most heart rate measuring systems, this is completely non-intrusive, and eye- and skin-safe, rendering it applicable for applications such as standard diagnostics, neonatal care and cardiology.

1. Introduction

Cardiovascular disease is the leading cause of death in Europe [1]. Monitoring heart rate and cardiovascular health can prevent deaths due to early diagnosis and the application of professional treatment. Current cardiac activity is quantified using a variety of devices from photoplethysmography (PPG) sensors to simple pulse oximeters and complex electrocardiography (ECG). ECG is a technique typically used in hospitals and by emergency response teams but it requires large machines that provide accurate heart rate readings while sacrificing portability. PPG sensors are commonly found on wearable technology such as smartwatches or chest straps. Current PPG sensors use LEDs to illuminate skin and obtain the PPG signal, the close proximity of the LEDs to the skin can cause damage (in a few cases, but not on a large scale). In the case of newborn babies, the skin is too sensitive to consider using direct contact PPG devices to measure heart rate [2], while also acknowledging that in these cases, fewer physical connections are an obvious advantage. With this motivation, I investigated and now present an attempt to measure heart rate, in transmission, without physical contact and lay the foundation for future investigations.

2. Background

Measuring the heart rate through finger vein scanning is a non-intrusive and non-contact alternative to pulse oximeters. Finger vein scanning is done by capturing a "shadow" image of the vasculature after near-infrared light propagates through the finger. This is possible as NIR light is absorbed by the blood, whereas it is mostly transmitted through tissue material [3]. Other features noticeable on a finger scan image are the inter-phalangeal joints. The area where the joints are appears lighter than those where the bone lies. This is because the joint is less dense than the bone.

In the field of finger vein scanning, much of the early research was motivated by biometric security and authentication. Various algorithms developed and applied to biometric security [4, 5, 6] have been applied in this research project for HR measurement.

2.1. Related Literature

Hoover *et al.* proposed a system for identifying veins in retina images using matched filters [7]. The process of creating a Match Filter Response image (MFR) involves convolution of the initial image, testing various candidate areas and comparing them to the set threshold, and then constructing the completed vein map of the retina. The algorithm, although not applicable for finger vein imaging, laid the foundation for future algorithms. The algorithm proved to be successful as it is claimed to have reduced the false positive rate by a factor of 15. However, the shortcomings of the algorithm are also stated, wherein thresholding may isolate groups of veins.

Lee *et al.* [6] [8] proposed a system to use local binary patterns to extract the features of the veins. In this publication, they proposed a hardware design which is more accessible and smaller. It incorporated a hot mirror which reflected the NIR light into the camera in a more compact packaging compared to previous works. The user inserts their finger underneath the LED and the light is reflected into the main body of the hardware towards the sensor. The objective of this paper was to convey a hardware design which is universally applicable and software which is more robust than any previous.

In the Lee *et al.* proposal the main motivations were biometric identification with an emphasis on speed. The disadvantages of other biometric identification systems are pointed out notably fingerprint reading. The main factors were finger and reader conditions with the presence of foreign matter obscuring the readability of the fingerprint.

The proposal illuminates the users finger with NIR LEDs and captures a series of images. Images were cropped and transformed to remove unwanted regions of the image such as the background and the tip of the finger where veins are not as present. The analysis used local binary pattern (LBP) where a 3x3 grid was placed upon a region and all the pixels were compared to each other in terms of brightness. The darkest ones were labelled as veins and then compared to their neighbours. The vein map was then built up and used to compare to a database for identification.

Gabor filters were proposed for use of ridge enhancement by Yang *et al.* [9]. In the paper, they claimed that no other system yet had been able to overcome the issues that arise from finger positioning. The main objective of their publication was to improve the robustness of the vein imaging system.

One of the major changes they made to the general hardware design was to add two more NIR LEDs. This increased the contrast between tissue and veins. The background of the image also contained guides to show where the middle section of the finger was. This was used to crop out the rest of the finger image as only the middle section of the finger between the two inter-phalangeal joints was analysed. Unlike the previous experimental design, this proposal utilises the background to indicate the region in which the analysis will be done.

The Yang *et al.* proposal uses several image-enhancing techniques before applying the Gabor filters to the image to map the veins. The filter itself uses the real part of a complex Gaussian wavelet to enhance the edges of the veins. They are then modified using multiscale multiplication.

Heart rate measurement techniques based on remote photoplethysmography (rPPG) [10] allow for long-range heart rate measurement compared to conventional methods such as pulse oximeters. rPPG detects the change in intensity of light from absorption in haemoglobin in the blood. The change in the rPPG signal can be used to calculate the heartbeat. Neural networks have been able to show the heart rate of a user with only two seconds of video [11].

The rPPG signals can be detected from increased range as seen by Yang *et al.* [12]. The proposed system is able to measure heart rate from a range of up to 4.5m by imaging the user's hand. rPPG signal analysis and passive heart rate measurements have many positive applications.

- Affective computation
- Deepfake recognition
- Long-range health analysis
- Driving condition monitoring
- Natural disaster survivor locations
- Infant vital signs monitoring
- Fitness and exercise tracking

Most rPPG methods use facial regions to obtain the signal [13]. This is due to the fact that most users interfacing with the technology will be facing the camera at the time of measurement and the lack of clothing obstructions.

2.2. Relevant Literature

Repeated line tracking for vein imaging was proposed by Miura *et al.* [4] in 2004. At the time biometric identification was not as widespread as now (with examples of this in today's phones capable of identification using faces and fingerprints). This was also one of the first applications and investigations into finger vein imaging using NIR light. The main idea was to create a system which can image veins and correctly match these images to reference ones. The proposal used iterative line tracking; a process of finding a vein and moving along that vein and labelling it as such. The process of identifying the vein starts with taking a cross-sectional view of a dark region. The veins in the monochromatic images form a 'valley' like profile. This is due to the outer edges of the vein being brighter (i.e. light propagates through the tissue but is absorbed by the blood in the blood vessels) and the pixel values being higher. The centres are then labelled and stored in the 'tracking space'. The algorithm moves along to the neighbouring pixel and the process is repeated. If the neighbouring pixels are not identified as veins the algorithm will start at another random point. As the algorithm iterates the higher the pixel tracking space value, the higher probability the pixel is part of a vein.

To try and reduce noise generated due to false labelling, an alternative to line tracking was proposed and investigated, wherein the starting point is chosen randomly each time [14]. Historically, line tracking would have a singular point to start from and branch out from there. Along with the noise, varying background conditions are challenges that were identified as the ambient light influences the quality of the image acquisition, and as a consequence, the mapping of vascular networks. The anatomical variability across individuals was also a challenge. Finger size, skin type and cardiovascular health are outlined as variations which have an impact on the vein image and an attempt was made to reduce the computation time to allow for wider applications. These challenges are a common problem for any finger vein imaging and are not limited to iterative line tracking or biometric authentication.

To test the robustness of the line tracking technique, Miura *et al.* investigated the system in varying lighting conditions. During these tests, they compare the results to the matched filter response algorithm. In high and low background light conditions, the line tracking outperformed the matched filter system. The ability of a vein tracking system to work in variable light conditions is important as the system was intended to be used in ambient light conditions.

Miura *et al.* [5] proposed another system to capture vein patterns with a different algorithm. This paper is an extension of previously discussed work, with many of the same motivations including biometric security. The main motivation is to improve upon previous work with a new approach, i.e. using maximum curvature points. The drawbacks of the line tracking algorithm approach include the inability to detect and monitor small and thin veins, in comparison to

(a) Hand Drawn (b) Repeated Line Tracking (c) Matched Filter

Figure 1: Vein pattern extracted using various methods [4]

larger vessels. This is important as, for biometrics, the complex network of vessels of varying sizes constitutes a unique pattern for security. In comparison to previous studies, the research uses the same experimental methodology to identify the veins.

The maximum curvature algorithm measures the vertical profile of pixel values across an image. This vertical profile covers the background and the vein, resulting in characteristic curves with 'valleys' representing the veins. Within the curves, the veins are described by the local minimum, points within the profile slice where the brightness drops. By moving along the image and sequentially identifying the vein centres, a map can be made by joining the centres. These sweeps can be done in various directions to build a more defined vein map. In the literature, and in this research study, 4 sweep directions (horizontal, vertical, and both 45° diagonals) are done.

The maximum curvature points algorithm was tested against line tracking and matched filters in differing background conditions. The tests used artificially created finger vein patterns to simulate different types of participants. The maximum curvature method outperformed the matched filters and line tracking in this test. The test was to see how well the vein tracking methods identified the smaller veins and how much noise was detected. It is worth noting that the line tracking still outperformed the matched filters as seen in the previous publication.

As opposed to the maximum curvature technique proposed by Miura *et al.* [5], the method proposed by Choi *et al.* [15] applies a normalised gradient field to the image before finding the Principal curvatures of the vein map. After the application of the gradient field the process of scanning through the image is the same as that of the Maximum Curvature proposal.

Developing a low-cost and robust device for remote heart rate measurement which can reliably measure in varying conditions was proposed by Kallepalli *et al.* [16]. The system uses line tracking and maximum curvature point algorithms developed for biometric security to map the veins of a user's finger. The main motivations of the paper were to create an easily accessible, low-cost system to remotely measure heart rate.

The vein images are compared by the width of the veins over a short period of time, and from that, the HR of the user is calculated. As opposed to previous methods of vein imaging, the proposed system uses red light as well as NIR. In the experimental tests, 12 people were used, having a range of different skin types.

3. Methods

The methodology in this study includes 4 key components: illumination strategy, conceptual understanding of near-infrared light and tissue interaction, imaging and finally, image processing and analysis.

3.1. Hardware

The hardware for this project was based on the ModLight system [17], with a few modifications. The design was made using OpenSCAD and printed using PLA on an Ultimaker S5 3D printer. The reason for picking 3D printing was the versatility it offers in terms of designing parts and continually evaluating them as the design process progresses. Compared to off-the-shelf components, which add delivery time and uncertainty with suitability, 3D printing the parts only took five hours for the largest components, which allowed for quick turnaround time in case the parts were unsuitable. OpenSCAD was used to design the parts due to its easy to use interface and code-based part assembly which meant changing of part dimensions did not interfere with any other features of the part.

The LED housing and modules were made based on the ModLight system [17], an open access optical device designed to provide a wide range of illumination options for a vast range of applications. The ModLight boxes are 3D printed and assembled using magnets to create a compact, reconfigurable, package for the standardised LED modules. In this device, the box is modified to hold two LEDs (red and NIR), and the metallic coated mirror is replaced with a ThorLabs FM03 cold mirror [18], used to reflect the red light into the same path of the NIR. This allows the lights to be switched alternatively whilst illuminating the same target on the finger. The cold mirror is a dichroic filter which allows transmission of light over $\lambda = 700nm$ and reflects wavelengths shorter than that. Hence, the NIR is transmitted and the red is reflected.

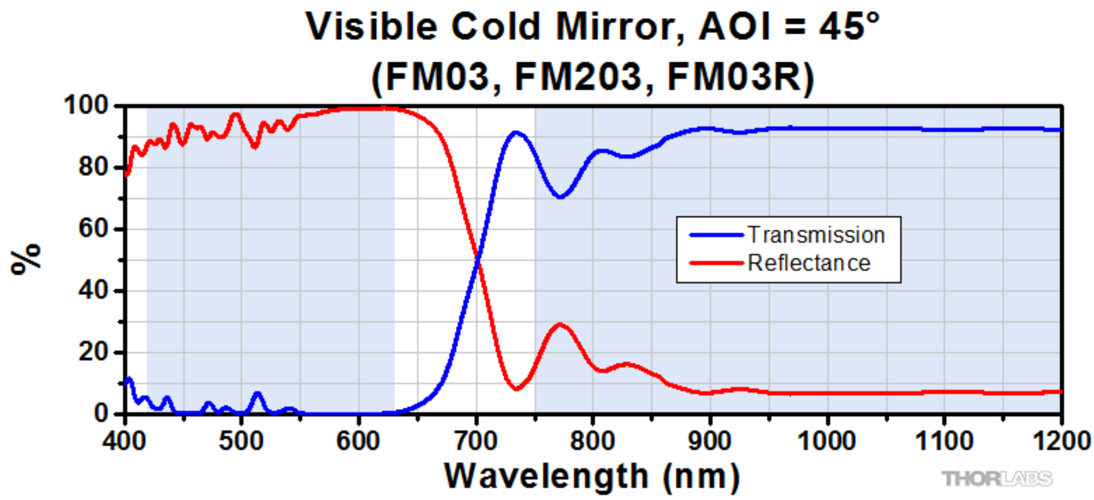


Figure 2: Transmission properties of the FM03 cold mirror used in the device [18].

The LEDs were controlled using LabVIEW and a Raspberry Pi Pico, a common microcontroller development board. The Pico was programmed to read text inputs via its serial port to switch the GPIO pins on and off. The GPIO pins were connected to separate LED drivers for the red and NIR, which were programmed to be turned on and off sequentially. The alternating LEDs allowed for a series of images to be captured with only one of the LEDs illuminating the subject. The LabVIEW program captured the images and labelled them according to which LED was on at the time of capture. The LabVIEW program allowed for a LED flickering frequency of 20 frames per second which allowed the sufficient temporal resolution to find the pulses in the vein widths.

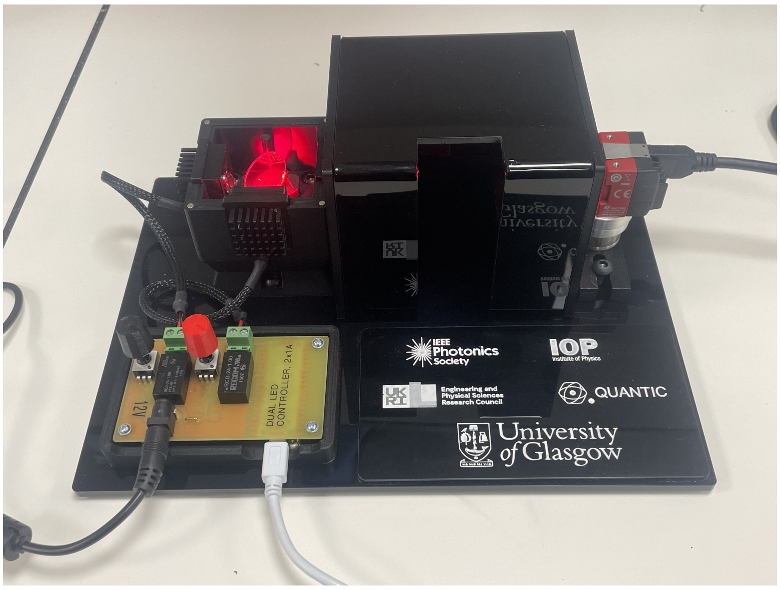


Figure 3: Complete imaging device, featuring Allied vision Alvuim 1200, LED control board with Raspberry Pi Pico connected to laptop, Illumination module, and the acquisition chamber.

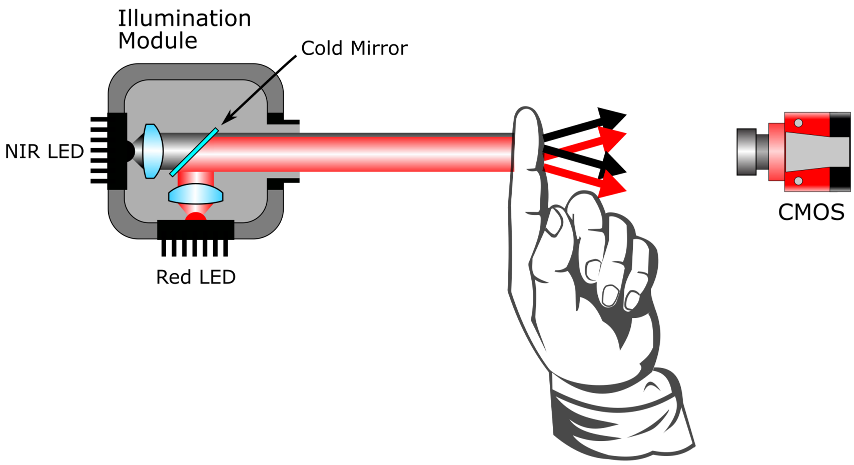


Figure 4: Diagram of hardware set up. The cold mirror directs both LED outputs towards the same point on the finger. The resulting diffusion of light is captured by the CMOS camera, Allied Vision Alvium 1200.

The camera used was the Allied Vision Alvium 1200. The monochrome sensor is able to capture visible and NIR light, which made it a suitable choice to use for the device. The camera was connected via USB to LabVIEW, in which the camera's exposure, capture rate, gain, and other attributes could be controlled. The lens had a 60° field of view and was mounted using an S-mount screw thread. The camera is mounted on a post at the same height as the output of the LED box on the other side of the acquisition chamber. The acquisition chamber was made from a black acrylic sheet, which was laser cut to accommodate a slot for the finger to be inserted. The sheet was thermoformed to fit over the 3D-printed end plates and the inside was lined with black cloth to prevent reflections. A guide for the finger was attached to the far side of the chamber opposite the gap for insertion. It was placed at the correct height so that the finger was positioned in the same plane as the camera and LED output.

3.2. Software

LabVIEW is used to control the camera and allows for user input to optimise the image quality before data acquisition begins. Users can position their finger in the acquisition chamber and adjust the LED brightness using the potentiometers on the PCB control unit. Changing the exposure on the camera whilst monitoring the maximum pixel value for the finger region, ensures that the sensor is not saturated and the data set will be high quality. The program allows to change the image acquisition rate, amount of images taken and format of images. The selected file format was.TIFF, which are high-quality image files which are not subject to lossless compression compared to other formats such as JPEG images.

The algorithms used to analyse the images were developed by B. Ton and are available for use on the MATLAB file exchange [19]. The functions are based on the algorithms outlined in the Miura papers [4][5]. As the finger was always in the same position due to the finger rest, the images were cropped to the same rectangle, to cut out the background of the acquisition chamber and the non-target fingers. The cropped images are then localised to just the finger using the Lee algorithm [8] which was developed for MATLAB by B. Ton [20]. The detected finger regions were then analysed using the repeated line tracking algorithm [4] and the maximum curvature technique [5][15]. The iterations, distance between the tracking point and cross-section of the profile, and profile width can all be changed for the Repeated line tracking algorithm. The value of sigma can be altered to desired values for maximum curvature.

The Vein width monitoring program reads each image and locates the peaks in a given vertical slice and for each input image appends the width of the vein. This is done using the MATLAB signal processing toolbox. The data is then smoothed using MATLAB peak smoothing and a Savitzky-Golay filter is applied [21].

(a) Original Finger Image

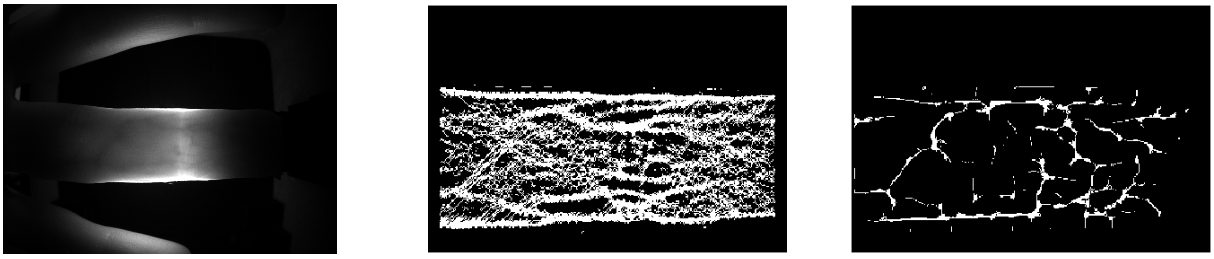
(b) Detected Finger Region

Figure 5: Lee Finger recognition algorithm. The algorithm compares the dark pixels of the background and the light pixels of the finger to form a mask which is used in the analysis algorithms to ensure it only executes on the finger region.[8] [20]

After the series of vein maps are produced, the images are analysed using morphological analysis methods [22], these are done to connect the vein centres in the images and remove unwanted noise. On the vein maps obtained via repeated line tracking, a median filter is applied to reduce noise, followed by morphological opening to remove speckle noise. On the vein maps obtained via maximum curvature analysis, morphological dilation is used to connect the vein centres by increasing their size, followed by a median filter to remove noise.

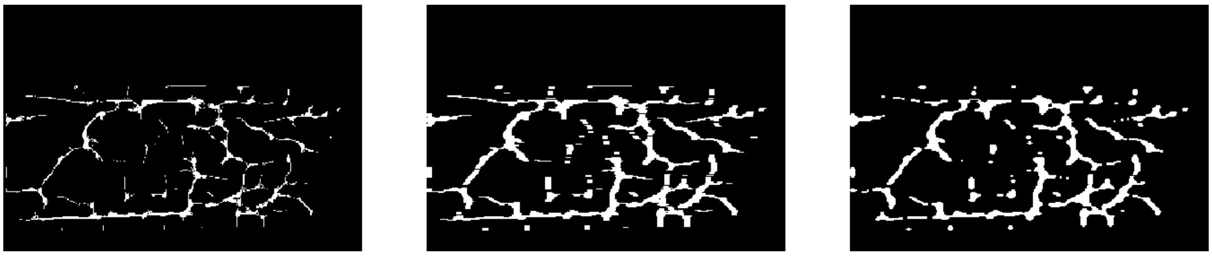
4. Results

A series of 2400 images were taken over a two-minute period at a constant rate of 20 frames per second. During the acquisition time, the user is wearing a pulse oximeter on the other hand to measure their heart rate. The images are saved to separate folders for NIR and Red images and labelled in the order they are taken. The MATLAB program then takes each folder respectively and applies both algorithms and the respective morphological operations before saving each image to a separate results folder.



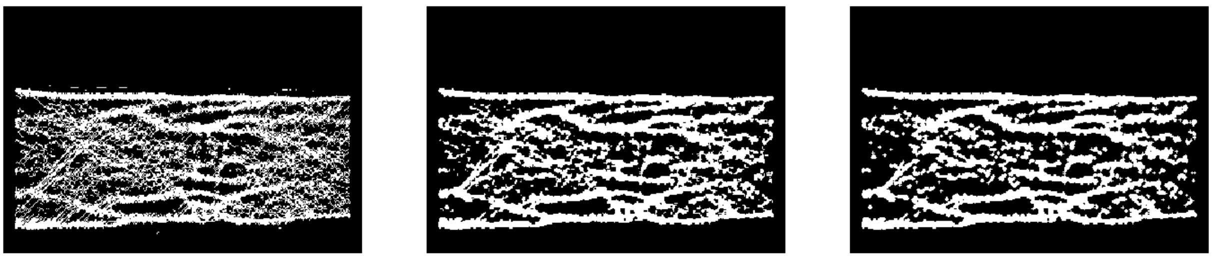
(a) Original Finger Image (b) Repeated Line tracking (c) Maximum Curvature

Figure 6: Vein Image before being analysed, and after with the repeated line tracking algorithm and maximum curvature analysis.



(a) Maximum Curvature (b) Image dilated (c) Median Filter applied

Figure 7: Process of morphological analysis for the maximum curvature vein map. The image is dilated and then a median filter applied to the dilated vein map.



(a) Repeated Line Tracking (b) Median Filter applied (c) Image Opened

Figure 8: Process of morphological analysis for the repeated line tracking vein map. A median filter is applied then, the image is opened.

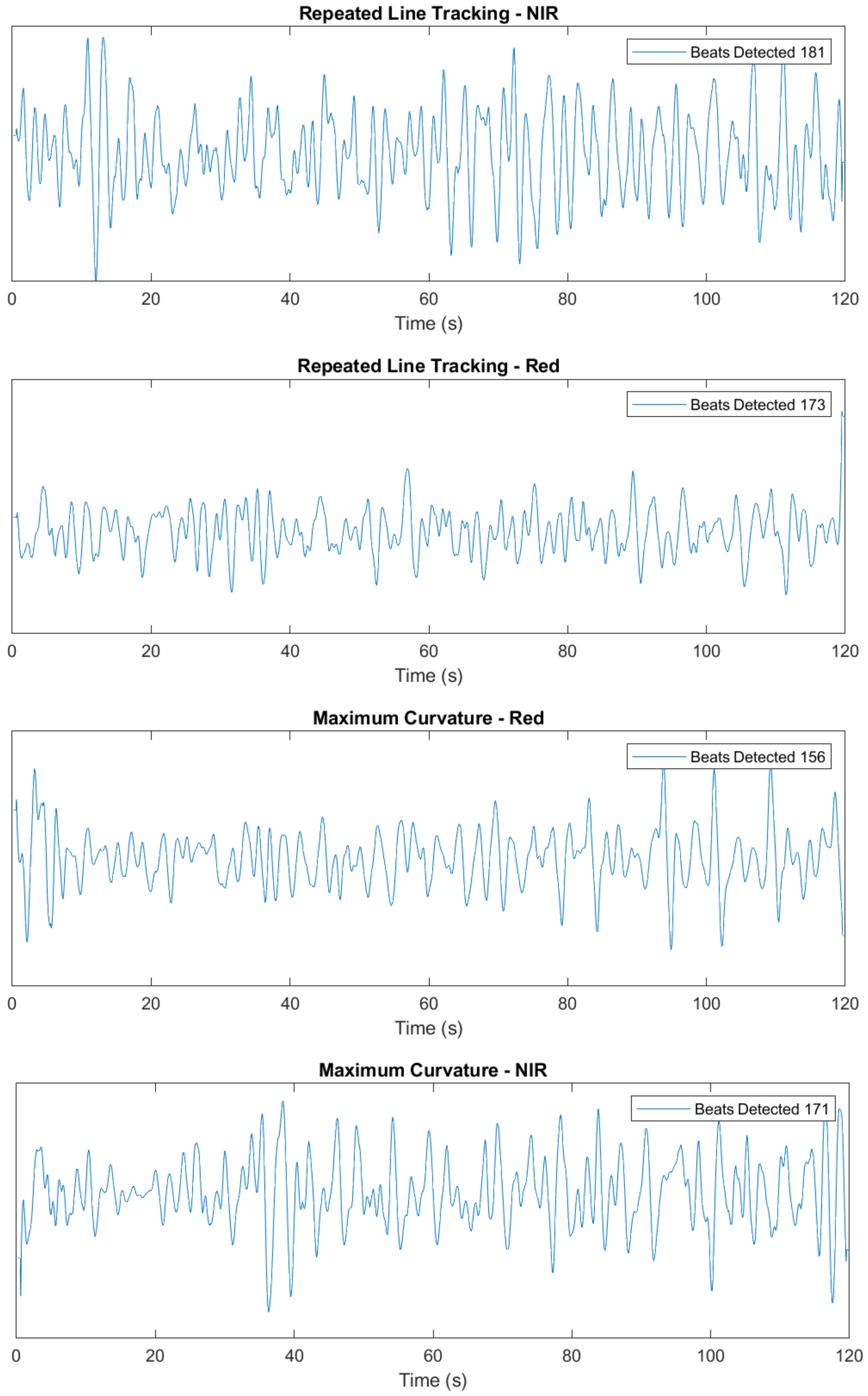


Figure 9: Measured cardiac activity measured from the two types of illumination, analysed by both algorithms.

The results folders were then read through by the width monitoring algorithm to find the vein and monitor its width over the series of images.

Whilst the acquisition was being taken, the user was wearing a pulse oximeter heart rate monitoring device, to compare to results of the width monitoring algorithm. The device used was the Berry BM2000A V2.1, which was placed on the right index finger whilst the left hand was inserted into the acquisition chamber. The heart rate of the user was measured to be 85 bpm at the time of measurement.

Illumination	Analysis technique	Beats detected	BPM	Difference to reference value
NIR	Repeated Line Tracking	181	90.5	+ 5.5
NIR	Maximum Curvature	171	85.5	+ 0.5
Red	Repeated Line Tracking	173	86.5	+ 1.5
Red	Maximum Curvature	156	78	- 7

The detected BPM was shown to work best with NIR and maximum curvature analysis, as it was closest to what was measured with the pulse oximeter. The average magnitude of near-infrared differences was closer to the reference value than the average magnitude of the red differences.

5. Discussion & Conclusion

The device successfully captured and analysed vein images for heart rate analysis. The device and software combined, are a low-cost and anti-intrusive alternative to pulse oximeters and other current heart rate monitors. The heart rate obtained from the device was not dissimilar to the pulse oximeter and shows that this type of measurement has the potential for clinical applications.

The two vein mapping algorithms used had varying performances and excelled in different ways. Repeated Line tracking identified the veins well but took longer per image, over the course of the 2400 images this took approximately five hours to process. Reducing the number of iterations would bring the processing time down, but the vein map quality would be lower. Maximum curvature had quicker processing times with the 2400 images being analysed in two hours, which was significantly less time than repeated line tracking. The images produced after the morphological analysis had less noise than the repeated line-tracking images, but the veins were less pronounced.

The usage of Python was investigated as an alternative to MATLAB, to allow for quicker integration into LabVIEW. LabVIEW has the ability to call Python functions in the VI's, providing real-time analysis of the images for vein width monitoring. Developing a Python equivalent to the MATLAB programs was done with the Bob toolbox, a set of machine learning algorithms for biometric analysis developed by the Biometrics Security and Privacy Group, the Biosignal Processing Group, and the Research and Development Engineers at Idiap [23]. [24]. Specifically, 'the bob.bio.vein' package provides functions to analyse images using repeated line tracking, maximum curvature, and the Lee mask. The functions were executed alongside NumPy [25], MatPlotLib [26] and other packages to optimise the images. The resulting images from Python were not as high quality as the MATLAB equivalent, specifically, the maximum curvature vein maps would have veins too large and the veins in the repeated line tracking vein maps were hard to identify compared to the noise. The Python program had the advantage of using code to install required packages at the start of the code, as opposed to MATLAB which requires the user to manually enter the add-on explorer and select the necessary packages.

The Pico was selected as its compact dimensions and micro-python interfacing allows for quick communication with the laptop via micro-USB. Since all that is required is the control of two LED drivers at a given frequency, the Pico is suitable for this application. The Raspberry Pi

Zero, Raspberry Pi 4, and various Arduino models would all be appropriate for this application, but the Pico is a fraction of the cost and more compact. The advantage of using a Raspberry Pi 4 or a similar chip would be to remove the need for connection to the PC and have the analysis done on the device board. This would require an LED display to communicate the result of the analysis to the user and real-time analysis. The device would not have the ability to control the parameters of image capture unless a screen with a user interface was connected.

Real-time analysis would make this device useful in many real-world applications. To achieve real-time heart rate estimation, the program would have to be able to run one of the algorithms as the images are captured, find the width of one of the veins and compare that to a previously computed value. These values would be analysed and a heart rate value could be found based on the last couple of seconds of images. A possible way that this could be done is through LabVIEW and Python, with images being analysed, vein width stored along with the time of capture, stored in the program, and the image cleared to save storage space. A possible problem with this could be the Raspberry Pi Pico's serial port getting saturated with commands from LabVIEW. During the initial configuration of the device it was noted that for long, high frequency data acquisition, the LEDs would flicker at an inconsistent rate and continue to sequentially switch at a rate close to 2 Hz after all the images have been captured. To fix this the Pico had to be unplugged and then reconnected again, this is the reason for going at 20 frames per second to avoid the Pico lagging behind. Using a higher cost chip such as a Raspberry Pi 4 would allow for communication through other means, such as the Ethernet connection port. This however would raise the total cost of the system significantly.

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