TECHNISCHE UNIVERSITÄT MÜNCHEN

DEPARTMENT OF INFORMATICS

Master's Thesis in Informatics

Vein Viewing System Using Hardware Extension Attached To Smartphones

Venenbeobachtungssystem mit Hardware-Erweiterung für Smartphones

Author:	Bakri Bitar
Supervisor:	Prof. Dr. Uwe Baumgarten
Advisor:	Prof. Dr. Uwe Baumgarten
Submission Date:	15.11.2018

I confirm that this master's thesis in informatics is my own work and I have documented all sources and material used.

Munich, 15.11.2018 Bakri Bitar

Acknowledgments

Abbreviations and Acronyms

API	Application Programming Interface
APK	Android PacKage
AAPT	Android Asset Packaging Tool
AR	Augmented Reality
EM	Electromagnetic
IDE	Integrated Development Environment
IR	Infrared
JRE	Java Runtime Environment
JVM	Java Virtual Machine
LED	Light Emitting Diode
NDK	Native Development Kit
NIR	Near-Infrared
OpenCV	Open Source Computer Vision Library
OpenGL	Open Graphics Library
OpenGL ES	OpenGL for Embedded Systems
OS	Operating System
OTG Cable	On The Go Cable
PCB	Printed Circuit Board
RBC	Red Blood Cell
SDK	Software Development Kit
US	Ultrasound
USB	Universal Serial Bus
UVC	USB Video Class
WBC	White Blood Cell

Abstract

The goal of this thesis is to develop a low-cost non-invasive vein viewing system on android smartphones that helps healthcare workers to identify the superficial veins, locate and examine them by providing an accurate AR image in a real-time manner. Venepuncture and starting an intravenous cannulation are frequently required skills in healthcare facilities for investigative or diagnostic purposes. Finding the right vein is a substantial prerequisite for such operations and could be time consuming, moreover, it is unfortunately not risk free as numerous associated complications have been described, including misplaced puncturing or even accidental arterial puncturing and cannulation, causing a life threat or unnecessary pain and stress to the patient in best cases. Dedicated devices for viewing and locating veins have been launched in the market, although they seem to give excellent results in terms of accuracy and performance, they include advanced and expensive hardware which makes them unaffordable for some countries or clinics.

The proposed solution includes a low-cost hardware extension attached to a smartphone and an android application that receives and processes data sent from sensors placed on the hardware extension. On the smartphone's screen, healthcare workers should be able to see a real-time video showing the superficial veins with good contrast and depending on that they can locate the veins and puncture them with much less probability of misplaced puncturing.

We used NIR, Near Infrared, light source in wavelength of 940 nm and light sources as LEDs placed on an electrical circuit along with a digital video camera that only senses light waves in the infrared spectrum, which we obtained by replacing the light filters in a normal web camera. Because of NIR light-absorption properties of the oxygenated blood, which is carried by the veins, we were able to increase the peripheral veins' contrast and, using image processing algorithms, visually isolate them on the received video in real-time.

Contents

1. Introduction

1.1. General Overview

In many clinical settings, obtaining intravenous access is an essential and routinely performed operation in medical procedures like blood sampling, collection, donation and intravenous therapy where some of these operations include a cannulation as well. Today, venepuncture procedures are conducted almost exclusively by trained clinical personnel. In this approach, the operator visually locates or palpates for a suitable vein and then introduces a cannula aiming to reach the center of the vein. The standard practice of using surface anatomy to identify vessels before cannulation is based on the presumed location of the vessel and the identification of skin anatomical landmarks. Oftentimes, however, it is difficult to find a suitable cannulation site, particularly in patients with small veins, dark skin, or a high body weight. When a vein is identified, it may also be difficult to estimate its depth or to accurately place the cannula if the vein moves. For these reasons, successful venepuncture depends heavily on the patient's physiological characteristics and the operator's experience and skill.

Depending on the cannulation site, manual techniques for peripheral vascular access have an overall success rate of 70 to 95% [14], [13]. The success rate can decrease below 50% in difficult populations, including paediatric, geriatric, and chronically-ill patients [25] . On average, difficult patients require three needle stick attempts per vessel, and the incidence of complications increases when more than three attempts are made by the same operator. venepuncture injuries due to multiple failed attempts significantly increase the likelihood of bruising, internal bleeding, acute pain, accidental puncture of nerves or arteries, and delays in medical treatment. The inaccurate placement of a peripheral catheter increases the chance of extravasation and tissue damage, and repeated failures may necessitate a switch to riskier and more costly interventions such as central venous access [14].

This solution utilizes a near-infrared light source to image the oxygenated haemoglobin in red blood cells, enabling a NIR-camera to capture a clear image of the superficial veins in real-time.

1.2. Complications Associated with Venepuncture

Several complications can arise during the peripheral venous access, the most common ones are described below and listed approximately in order of their frequency of occurrence [21], [15].

Pain

Needle pain is commonly reported by patients as the worst of all healthcare issues and might result in stress symptoms, tension, and onset of needle phobia. Avoidance of healthcare visits, for example for ordinary blood tests or immunization, is strongly related to the fear of needle pain. pain is even more feared when multiple needle insertions are needed, as an example, in difficult populations or when complications such as hematoma and nerve puncture occur.

Failure to Access the Vein

Wrong needle placing, incorrect angle of penetration, inadequate skin traction, or vein collapse can cause a failed attempt at gaining access to the vein. In this situation, many insertions are needed, either on the same place or, if the vein or the skin is compromised, at a another one.

Hematoma

Hematomas are one of the most common complications associated with peripheral venous access and are usually formed when blood leaks out of the vessel into the surrounding tissues. Hematomas are caused by a damage to the wall of the vessel through puncture and can be noticed under the skin as a massive bruise. The bruise causes discomfort and pain and can cause further complications. Hematomas are mainly common in children and elderly patients. In children, small vessels can easily be damaged or rupture if the needle tip punctures the posterior wall. In elderly patients, vessels become weak because of hardening of the vessel wall, which will increase the chance of vein rupture.

Unintended Arterial Puncture

Sometimes, it may be difficult to differentiate arteries from veins. Usually, healthcare workers avoid accidental arterial puncture by palpating the vein carefully to make sure that there's no detectable pulse before inserting the needle. However, it is harder to detect palpation, and arteries can be easily mistaken as veins in young children and obese patients. When an accidental arterial puncture occurs and is not identified, the delivery of intravenous fluids such as medicines into the arterial circulation can cause serious complications [35].

Peripheral Nerve Damage

Accidental puncture of nerves is rare but can happen when the nerves are located near a vessel [32]. It occurs most often if the needle is not accurately inserted in the vessel, or if the vessel moves away from the puncturing point after penetrating the skin and causes the needle to puncture an adjacent nerve. Nerves in the antecubital fossa area lie just beneath, and near the veins making them vulnerable to injury [32]. The best site for venepuncture of superficial veins of the upper limbs is the median cubital vein which lies over the cubital fossa and serves as a connection between the cephalic and basilic veins. That makes the median nerve particularly prone to accidental puncture, as it is located just after the basilic vein in the antecubital fossa and can lead to acute pain, numbness, or even, in rare cases, temporary paralysis in the region of the cannulation site.

Phlebitis

Inflammation of the veins, which can occur because of an accidental puncture of the posterior vessel wall or the rupture of the side walls during puncturing or cannulation insertion. mainly when delivering medications, movements of the needle or catheter can irritate the vessel. Phlebitis can be recognized by some usual symptoms like pain, swelling, redness, and tenderness and it can produce extreme medical complications if not detected.

1.3. Background: Infrared Radiation

Light Spectrum

The light or electromagnetic spectrum is a range of all types of EM radiation and it describes all the wavelengths of light. The EM spectrum, as shown in Figure 1.1 [42], is generally divided into seven regions, ordered by decreasing wavelength and increasing energy and frequency: radio waves, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays and gamma rays.

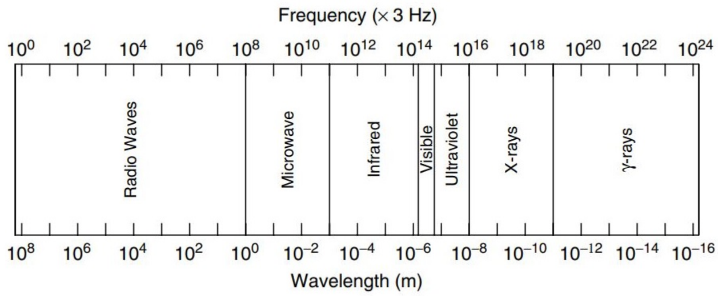

Figure 1.1.: The electromagnetic radiation spectrum.

Infrared Radiation

Infrared radiation is a region of the EM radiation spectrum where wavelengths range from about 700 nm to 1 mm. Infrared waves are longer than those of visible light, but shorter than those of radio waves. Infrared light is invisible to the human eye, but longer infrared waves can be sensed as heat and it shares some characteristics with visible light, infrared light can be focused, reflected and polarized. Based on wavelength, infrared can be divided into multiple spectral regions near-, mid- and far-infrared where the boundaries between them are not agreed upon and can vary.

The near-IR band contains the range of wavelengths closest to the red end of the visible light spectrum. It consists of the wavelengths from 700 nm to 1,300 nm. This group consists of the longest wavelengths and shortest frequencies, and it produces the least heat.

The intermediate IR band, also called the mid-IR band, covers wavelengths ranging from 1,300 nm to 3,000 nm. Wavelengths in the far-IR band, which are closest to microwaves, extend from 3,000 nm to 1 mm. This group consists of the shortest wavelengths and longest frequencies, and it produces the most heat.

1.4. Previous Findings

Due of the challenges associated with venepuncture, development of imaging technology has become essential. In this area, two non-invasive methods are commonly used: ultrasound (US) signals and near-infrared (NIR) light. The focus in this work is on NIR imaging. In this section, previous findings are described and discussed as well as the difference between US and NIR imaging techniques and reasons for choosing NIR over US imaging.

1.4.1. Ultrasound vs. Near-Infrared Imaging

Ultrasound Imaging

Using US can provide visual information of the size and depth of blood vessels, which could enable insertion of the needle in real time. In comparison with light waves (including NIR waves), acoustic waves can penetrate deeper into human tissue, allowing both superficial and deep tissues to be visualized.

The use of US imaging has shown potential to improve the success of cannula insertion and Reducing complications. They are appropriate for imaging vascular structures and surrounding areas, usually, using 2D imaging, Doppler colour flow, and Spectral Doppler. The main feature of the US over NIR light imaging is the ability to image tissue laying far beneath the penetration limits of NIR light.

Although, the size and cost of US imaging devices have been reduced in recent years, NIR imaging is more effective in terms of ease-of-use and has way shorter learning curve. Using the US, the operator must be able to interpret the two-dimensional images of the vessels and distinguish it from surrounding structures. However, this technique requires a high coordination between hand and eye to scan and insert the needle simultaneously according the live images. Though the use of the colour Doppler can confirm the presence and direction of blood flow, it requires an understanding of the mechanisms of Doppler image generation as well as performing the 3D task of placing a needle or catheter into a vessel based on 2D images and not to mention the fact that the transducer must stay in contact with the examined person's skin at all times.

Additionally, to visualize the needle inside the image, the operator holds the transducer parallel with the vessel then align the needle parallel to the imaging plane and the vessel and maintain the needle in the plane as it is inserted into the vessel. Deviations of 1 or 2 mm will cause the needle to disappear from the image. If the vessel rolls far from the image plane, it can also become invisible. Patient movement will likewise cause significant image distortions and make it difficult to maintain the visibility of needle and the vessel. Thus, it's far very hard to visualize the needle as it punctures the vessel, and hence the operator is left to infer the needle motion primarily based on the motion of the vessel.

Near-Infrared Imaging

NIR involves the projection of light on the skin. NIR light operates typically within the wavelength range from 700 to 1000 nm. Compared to visible light, NIR waves penetrate more deeply into scattering tissues because of low absorption and scattering rates of light through skin tissues at NIR wavelengths. NIR can allow monitoring of vessels up to 3 mm under the skin and thus provide good contrast and visualization.

NIR imaging depends on the fact that NIR can penetrate the skin and then haemoglobin in the veins absorbs it, structuring an image of the vascular pattern which is invisible to human eye but can be captured by an NIR camera. The images from the camera are then processed and displayed in real time either on a screen or projected back onto the patient's skin and thus providing a good visualization of the veins structure. NIR transmitters must not make any contact with the skin and are therefore easier to use compared to US transducers. Moreover, because the images are acquired in a top-down manner, difficulties related to the vessel or the needle disappearing from the image are avoided.

However, NIR imaging have some limitations. The major limitation is the maximum possible imaging depth. All vessels laying more than 3 mm in depth cannot be visualized due to penetration limitation of the NIR light. That makes NIR imaging less usable for patients with special skin conditions like skin diseases or scars that increase the skin thickness or for patients with high body weight.

Another limitation of the NIR imaging is that the 2D images don't provide information about the depth of the vessel and thus cannot inform the operator about whether the needle has penetrated the vessel and punctured the posterior vessel wall for example. This is important because many of the adverse events that occur during cannulation, including poor sample collection and hematoma occur mostly due to posterior wall puncture. Lastly, it could be difficult to differentiate arteries from veins using NIR imaging, especially in obese patients or children where the pulse in the arteries is more difficult to be identified via palpation. Because of these limitations, NIR imaging devices can mainly be used to approximate the location of the vein. The cannulation itself should be performed without NIR guidance.

Conclusion

Both US and NIR imaging techniques have features and limitations and depending on problem specifications, one can choose the suitable technique. NIR technique is better for a simple 2D imaging and it comes with a feature that no contact with the skin is needed and it is easier to use especially for relatively untrained personal, on the other side, US technique is preferred for more complex situations as it offers a 3D visualization of the veins pattern and it can penetrate more deeply than NIR but it requires eye-hand-coordination skills and a founded knowledge about Doppler image generation. We focused on the NIR imaging, due to the shorter learning curve and ease-of-use of it and because of the fact that the main focus is to develop a simple low-cost vein-viewing mobile system.

1.4.2. Studies and Products

In this area, a lot of studies have taken place and a lot of products have been developed in the last years. While some of the prototypes and products developed give promising results, they are either too big to be handheld and portable or too expensive because of the advanced technologies utilized in them. Below is a brief list of studies and methods used in some products.

Studies

The shared drawback between the studies in this field ,as in [2] and [40], is that a computer must be used to process the data coming from the NIR camera, which lacks portability as it can just run on a computer which is not as portable as mobile phone and more importantly it lacks usability because it's hard to use a computer as AIR aiding device in such case as one needs to look at the computer screen and the examined limb at the same time which is not the case when using a mobile smartphone just above the examination area.

Dedicated Devices

Dedicated devices for viewing and locating veins have been launched in the market, a lot of them use NIR light and NIR cameras, while some of them show the results as projected light directly on the examined limb as hologram, others show them on a screen. Although they seem to give excellent results in terms of accuracy and performance, they include advanced and expensive hardware which makes them unaffordable for every healthcare worker.

USB NIR Cameras

An NIR camera which can be connected to a normal computer via USB where a windows application shows a real-time video of the limb with contrast of the superficial veins, although the result seems to be fair but as in the dedicated devices, it suffers from the lack of portability and usability.

NIR Transilluminators

Usually devices with plastic ring-shaped head where high power NIR as well as red visible light emitters are placed, results are examined then with naked eye, results seem to be adequate when examining healthy light skin-color people, but results are going to be inadequate when examining dark skin-color people or those with some special skin conditions as the used technique is strongly dependant on such factors.

2. Skin- and Blood-Light Interaction

2.1. Skin-Light Interaction

The relationship between an optical radiation and human skin depends on the absorption and scattering properties of three skin layers, listing from the outside: epidermis, dermis, and hypodermis [7].

The structures and component chromophores of these layers determine the behaviour of radiation. Understanding the penetration of optical radiation can be achieved by studying and analysing the wavelength-dependent interactions of light with skin. For example, melanin exhibits maximum absorption in the UV and blue spectral ranges, whereas blood absorbs blue and yellow light. The chromophores, such as melanin, blood, water, and lipid determine skin absorption [5]. We will focus on the epidermis and dermis as the blood vessels are contained in the dermis

Absorption and Scattering Properties of Epidermis and Dermis in The NIR Spectrum

As the outermost skin layer, the epidermis forms the actual protective covering against environmental influences. The average thickness of epidermis is approximately 0.1 mm. However, on the face it maybe as thin as 0.02 mm, while on the soles of the feet it is as thick as 1–5 mm. Absorption and scattering of epidermis in the visible and NIR spectral ranges are defined almost exclusively by its melanin, the protein that adds pigment to skin, and water contents, respectively [5].

The next layer is dermis, it is composed of gel-like and elastic materials, water, and, primarily, collagen. Embedded in this layer are systems and structures like lymph channels, blood vessels, nerve fibres, and muscle cells. Blood and water content define the absorptive properties of dermis in the visible and NIR range[5].

Absorption and scattering coefficients of skin layers are shown in Figure 2.1 and Figure 2.2 below [5]. The graphs demonstrate that the scattering and absorption of the first two skin layers decrease with the increasing wavelength. Which means light transmission increases with increasing wavelength.

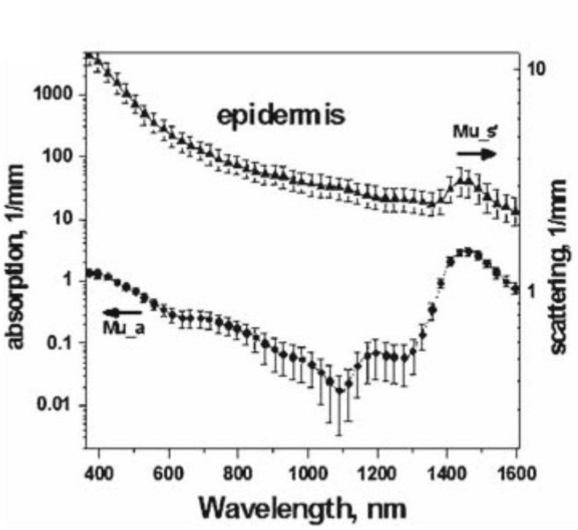

Figure 2.1.: Optical properties of epidermis, Triangles – reduced scattering coefficients, circles absorption coefficients, bars – standard errors. Averaged over 7 samples.

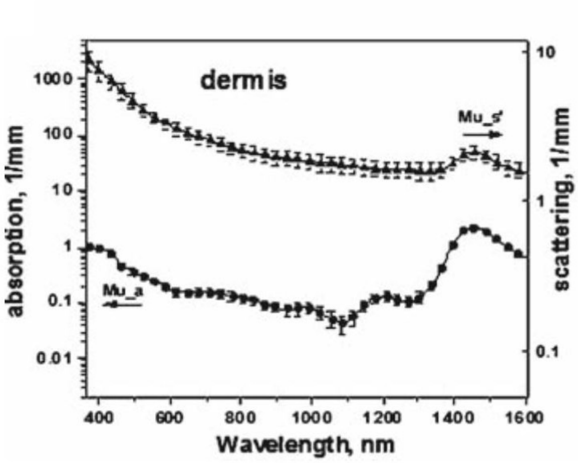

Figure 2.2.: Optical properties of dermis. Triangles – reduced scattering coefficients, circles absorption coefficients, bars – standard errors. Averaged over 8 samples.

2.2. Blood-Light Interaction

The optical properties of human blood under normal physiological conditions are largely determined by light interactions with plasma and red blood cells [43], which account for 99% of the cellular elements [20]. The effects of the optical properties of WBCs and platelets on the light scattering and absorption by whole blood are considered negligible [43].

Absorption and Scattering Properties of Red Blood Cells in the NIR Spectrum

Red blood cells have a thin plasma membrane that encloses mainly a haemoglobin solution. The absorption and scattering of light by the RBCs are two to three orders of magnitude higher than those of the other blood components [20]. The light scattered by a single RBC depends on its shape, volume, refractive index and orientation [20]. However, the absorption of light by the RBCs is dominated by haemoglobin in its functional, oxygen-binding, forms, namely oxyhaemoglobin and deoxyhaemoglobin. The Figure 2.3 below shows a remarkable difference in absorption rates between oxygenated and deoxygenated blood within the wavelength range from 800 to 1150 nm.

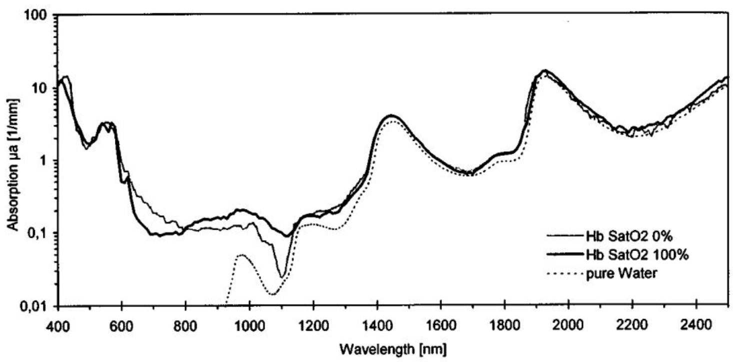

Figure 2.3.: The absorption spectrum of oxygenated and deoxygenated diluted blood.

2.3. Conclusion: Wavelength Selection

The goal of studying skin- and blood-light interaction is to analyse the absorption and scattering properties in both skin and light and eventually select the optimal wavelength to be used in the hardware extension. In summary, the optimal wavelength is the one that maximizes the skin, specifically the first layer, the epidermis, penetration, as well as the absorption of oxygenated blood, specifically oxyhaemoglobin. Due to the fact the veins carry only oxygenated blood, the selected wavelength should also maximize the difference in absorption rates between oxygenated and deoxygenated blood, which can enhance the contrast and the overall result. It is necessary to take into account the optical path of light traveling from the light source through the first skin layer, the epidermis, and then through the dermis which contains the vessels. The light is then absorbed by the haemoglobin in RBCs in the oxygenated blood carried through the veins, but reflected/ scattered by the surrounding tissues.

The maximum value of epidermis light penetration is equivalent to the minimum value of light absorption. The graph Figure 2.1 shows that the absorption of epidermis decreases with increasing wavelength and has minima at wavelength 1100nm.

The Figure 2.3 demonstrates a maximum absorption value of blood at wavelengths 1500 and 2000 nm but as shown in Figure 2.1 the light will not reach the blood or even the dermis at all as of the increased absorption of the epidermis at these wavelengths. Additionally, there is no difference in absorption between oxygenated and deoxygenated blood at these wavelengths.

Following from the discussion above, the wavelength in which the light can penetrate the epidermis but gets absorbed by oxyhaemoglobin lies in the range from 800 to 1100 nm, optimally at 1100nm.

3. Hardware Extension

The hardware extension used in this project is composed of basically light transmitters that project the NIR light on the patient's skin and a light sensor that receives the reflected light from the skin and the underlying vessels and tissues and sends it to an android device connected to it via an on-the-go (OTG) cable.

3.1. On-The-Go Cable

3.1.1. Background

Many of portable devices would benefit from being able to communicate to each other over the USB interface, yet certain aspects of USB make this difficult to achieve such as storage for a large number of device drivers and the ability to source a large current [30]. The OTG (On The Go) specification as a supplement to the USB 2.0 specification was developed to allow a portable device to take on the role of a limited USB host, without the burden of supporting all the functions of a PC. USB OTG is a known USB standard which was designed to allow peripheral attachment to such items as mice, keyboard, memory sticks etc to small, mobile devices.

In addition to being a fully compliant USB 2.0 peripheral, an On-The-Go device must include other features and characteristics including, but not limited to, full-speed operation as a peripheral as well as a host, targeted Peripheral List, session request protocol and means for communicating messages to the user [30].

3.1.2. Power Providing Specifications

When an A-device (hosting device) is providing power on a port, it is required to maintain an output voltage within a specified range on that port, under loads of 0 mA up to the rated per port output of the device's supply as long as the rated output of the A-device is less than or equal to 100 mA [30].

If the current rating per port of the A-device is greater than 100 mA, then the voltage regulation is required to be between 4.75 V and 5.25 V, and the A-device is required to meet the USB 2.0 specification requirements for power providers [30].

3.2. Light Emitting Diodes

3.2.1. Background

Light-emitting diode (LED) is a semiconductor device. It consists of a chip of semiconducting material treated to create a structure called a p–n (positive–negative) junction. When connected to a power source, current flows from the p-side or anode to the n-side or cathode, but not in the reverse direction. Charge carriers (electrons and electron holes) flow into the junction from electrodes. When an electron meets a hole, it returns to a lower energy state and releases the energy in the form of a photon (light) [36]. The specific wavelength or colour emitted by the LED depends on the semiconductor used. The LED light output power ranges from milliwatts to watts. Their typical light beam divergence is approximately ± 120 degrees. However, it can be as small as approximately ± 5 degrees for the special constructions [36]. LEDs are very cheap and popular light sources. They are widely used in photomedicine. LEDs convert electrical energy to light with high efficiency and have a long lifetime. They are available in a wide range of wavelengths from UV to IR, including multicolour and white light LEDs.

3.2.2. LED Usage in The Project

According to the previous chapter, the optimal wavelength should be between 800 and 1100 nm, optimally 1100nm. For prototyping purposes, we used a wavelength of 940 nm as it is more available and cheaper in the market. The light beam divergence was estimated optically without taking it into consideration in the research.

To increase the output light power and distribution, a grid of 8 NIR LEDs was used. Each LED is of type SD-AR512C9, voltage 1.2-1.3V, wavelength 940 nm, angle of radiation 60 degrees and current 40mA, connected on parallel with a resistor for each LED.

The reason why every LED is connected to one separated resistor and not one resistor for all of them is that, when we use one resistor, we have a current limit for the whole LEDs section. After that it's up to each diode to control the current that goes through it. The problem is that real world diodes don't have same characteristics and therefore there's a danger that one diode will start conducting while others won't, which causes one LED to allow more current to flow than it can handle and burn up, eventually then, all other LEDs are going to overheat and burn up because of extra current flowing through them.

A resistor with 100 Ω is typically sufficient. As this value should be slightly higher than the minimum resistor value at which the LED has maximum illumination, this can be calculated by Ohm's low as follows:

$$R = \frac{(V_s - V_{LED})}{I_{LED}} = \frac{(5 - 1.2)}{0.04} = 95\Omega \tag{3.1}$$

where:

- V_S is the source voltage, measured in volts (V),
- V_{LED} is the voltage drop across the LED, measured in volts (V),
- I_{LED} is the current through the LED, measured in Amperes (A), and
- R is the resistance, measured in Ohms (Ω).

To control the illumination of the LEDs so that user can dim them or even turn them off, a stepless variable resistor was added on the whole set of the LEDs so that the current running in the whole LEDs section can be changed and, thus, their brightness. This element is not of much importance because it only adds small value to the overall project, for this reason the resistor's value was estimated based on practical test.

3.3. NIR Camera

Cameras are just clever light detectors. Through a sensor, different levels of red, green and blue light are detected and converted into a digital signal, creating an image as the one seen by the human eye. However, infrared and ultraviolet light are present in daylight but cannot be seen by humans. Unlike human eyes, camera sensors can detect NIR light. Infrared light can affect the colour reproduction drastically. To make the image more akin to what humans can see, most cameras are fitted with an IR-Cut filter which only allows visible light to pass through, reflecting unwanted infrared.

For NIR imaging, exactly the other way around is needed, i.e. passing only NIR light and filtering out any other wavelengths of the EM spectrum. So that any reflections caused by visible light from the epidermis can be out filtered and getting only the image that shows where oxyhaemoglobin has absorbed the NIR light and thus, getting a visual representation of the veins structure. Replacing the IR-Cut filter with IR-Pass filter is sufficient to achieve this goal.

We used a webcam of type Trust Exis with 640*320 resolution, after removing the IR cut filter and installing a 9mm NIR pass filter, theoretically, any normal web camera should work after replacing the filter.

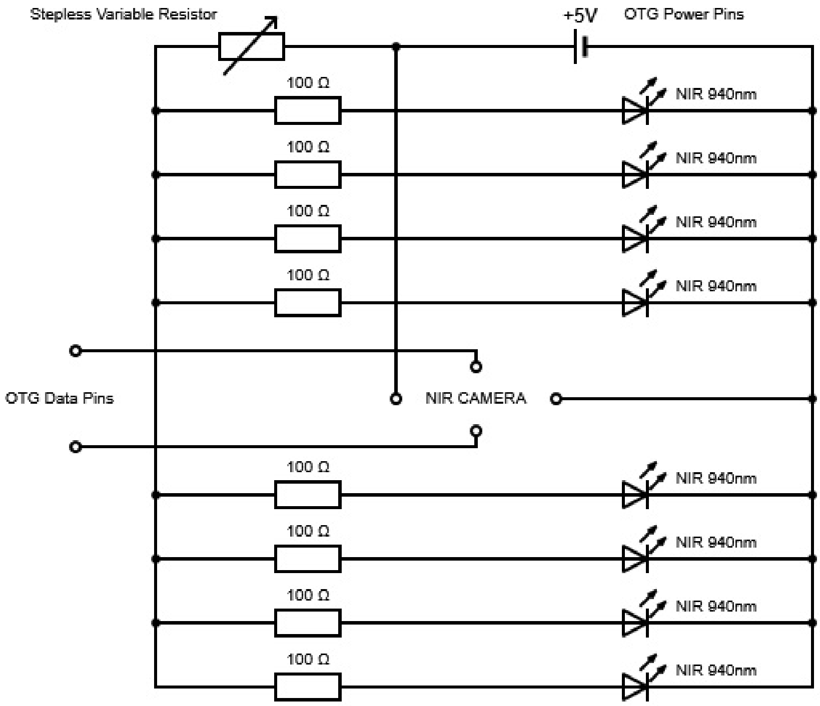

Figure 3.1.: The LEDs grid and NIR camera circuit.

3.4. Power Consumption

Android devices, especially phones, are powered from batteries which are limited in size and therefore capacity. This implies that a correct energy management is essential in any application running on such devices. Particularly, when the application includes a hardware part powered from the device and thus consumes more energy from the its battery. In this case, energy efficiency of the hardware part is crucial to the application usability or even feasibility at all.

When it comes to USB power, including the OTG, there are two device categories: bus-powered and self-powered. Bus-power is one of the many benefits of a USB design. It allows the device to sustain itself without the need for a bulky power supply either internally or externally because the device draws its power from the bus [28]. There are two classifications for a bus-powered device: high-powered and low powered devices. A low-powered device draws, at most, 100 mA and a high-powered device draws, at most, 500 mA. Anything over 500 mA requires the device to be self-powered [28].

As mentioned in the OTG section, the OTG protocol is fully USB 2.0 compliant and thus, its power providing in the high-powered device mode follows the USB 2.0 specification. Which means OTG cable can provide, at most, 500 mA. Hence, this value is the maximum power consumption limit and cannot be exceeded.

The overall power consumption of the hardware extension can be simply calculated as follows: Overall Consumption = Consumption of 8 LEDs + Consumption of the NIR camera , where the consumption of:

- 8 LEDs = 8 * 40 = 320 mA
- a normal Web camera ranges between 120 and 175 mA

Thus, the overall consumption is less than 500 mA, one can reduce the LEDs number to 6 in case that the web camera consumes more energy.

3.5. Heat Emission and Safety

IR light is generally safe. However, its safety must be reconsidered for such specific usages of it. It is unperceived by any of the human senses, unless from a heat stimulus resulting from high intensity. In general, IR radiation is classified as nonionizing radiation. Although its energy is deficient for ionizations, it may cause diverse biological effects of thermal origin [23]. Safety of the NIR light should be taken into consideration from two perspectives: eye safety and skin safety.

3.5.1. Skin Safety Assessment

The main cause of the potential hazard for NIR light projected on the skin is the heating effect. When NIR light is emitted by an LED without a direct contact, heat is transferred via NIR radiation and absorbed by the skin. However, temperature increase due to the radiated energy has been quantified to be less than 0.5 degrees [8]. Which, obviously, can be neglected in this study.

Conducted energy, which is caused by the temperature increase in the semiconductor junction inside the LED, can heat up the skin when there is a direct contact and cause temperature increases of up to 9 degrees for contact durations of 30 mins or more [8].

3.5.2. Eye Safety Assessment

The eye lens focusses the light on the retina. Focused light is stronger in terms of irradiance than non-focused light. Hence, injury potential increases with focusing.

In addition, NIR light initiates a very low, or non, visual stimulus. For example, one can look right into an NIR light source without knowing and the defensive mechanisms that typically shields the eye from excessive irradiation are not activated.

However, LEDs have been regarded safe for eye exposure by a number of studies from a radiated energy perspective [41] [17]. So, damage by NIR radiation is caused primarily by the overheating of the irradiated tissue, resulting in the destruction of cells. This can cause, for example, a permanent vision handicap [19] if direct and intense beam was aimed to the eye. The prototype includes a protective mechanism, so that the user knows that the NIR LEDs should be always kept facing down. An alarm rings if the device is flipped upside down.

3.5.3. Practical Assessments

Three practical assessments of the prototype's temperature increasement and power consumption were performed. The prototype was tested using an old Samsung Galaxy J5 phone. Each assessment was done in the room temperature and for a time duration of 10 minutes and caused a 5% battery drop.

In the first assessment, only the LEDs were left on with full brightness, but the application was not running. It yielded a temperature increase from outside of the device (temperature of one NIR LED) of 3 degrees.

The goal of the second assessment was to test the inner temperature of the prototype. A thermometer was placed inside the prototype. It yielded a temperature increase from inside of the device of 7 degrees which is relatively high.

In the third assessment, the image processing module worked for the whole time period as well as the NIR LEDs in full brightness and the camera. Analogously to the second assessment, a thermometer was also placed inside the prototype. The goal of this assessment is to test the power consumption of the overall system when image processing is on. Result of this assessment was 7 degrees of temperature increment.

3.5.4. Conclusion

- NIR light is safe for projection on the skin. The main hazard is the heating affect. Which can be neglected in the project setting as the LEDs power is very low.
- NIR light can be considered safe for eyes as well, but it is not recommended to aim any kind of directed light beam directly in the eyes.
- As per the practical assessments, power consumption is reasonable. But the prototype heats up relatively on continuous usage, this can be solved by enhancement of the plastic cover or adding a heat sink.

- The main power consuming component is the NIR LEDs. Those can be turned off without affecting the imaging quality, given sufficient daylight or at least reflection of it, is available, because the sunlight offers enough amounts of infrared light.

3.6. Device Compatibility

Unfortunately, having an OTG port is not enough to guaranty that UVC compliant camera will work well under Android. UVC is a standard class for USB video cameras and it will be explained later in a separated section. For reasons related to hardware and chip compatibility, not all android devices can run UVC compliant cameras.

Moreover, some manufacturers configure their Android image so that devices other than keyboard and mass storage are ignored, and this configuration is hard to detect.

As no official documentation for the UVC is available, android device compatibility can be checked by installing the app, or any other UVC camera app like CameraFi, and check whether it works. A list of compatible and incompatible devices as well as verified cameras can be found in the appendices.

4. Software Application

4.1. Methodology

The main focus is to develop a low-cost mobile system to locate and examine veins. As one can infer from the design of the hardware extension from the previous chapter, the cost of the hardware components is mainly the cost of a normal webcam, NIR-pass filter, a PCB breadboard and a set of NIR LEDs. Obviously, the cost of these elements is very low (under 30 Euros). The second component is the software application. In order to maintain the low-cost constraint, the software application must be run on normal android mobiles or tablets. Not on special hardware or expensive embedded systems.

4.1.1. Control of Hardware Extension

The hardware extension is connected as a peripheral to an android device. In that sense, the android device takes over control of the hardware peripheral in somehow. This control can be described as power control and camera control.

Power Control

Only a single connection via OTG cable is needed. Data and power are then transferred using the data and power pins of the OTG connection respectively. Power is supplied whenever the OTG cable is plugged in. No programmable way for cutting off power was implemented. Because turning off the host port's power needs write permission on the `/sys` directory and this cannot be acquired without root. The application is developed to be fully runnable on not rooted devices, so it requires no root access. For these reasons, controlling the OTG connection programmatically was out of the scope of this project. Of course, a physical switch can be also added on the whole circuit to turn the system on or off.

Camera Control

A third-party library, UVC Camera library, was used in this project to enable the android device to communicate with the webcam. UVC Camera supports variety of camera properties control like brightness, contrast, focus control and more, given that the camera itself supports those. Support is indicated by flags that the camera provides. Control of such properties can be done in the C++ side. Signals are sent from the module to the camera to change sensor values. For example, brightness and contrast control were added in the project. In this case, brightness and contrast are controlled by changing some sensor values, without the need of using image processing at all.

As per the UVC specification, if the auto setting is supported and set to the on state, the device will provide automatic focus adjustment, and read requests will reflect the automatically set value [37]. Attempts to programmatically set the Focus control are ignored when auto mode is set. When the UVC Camera library detects an autofocus support in a connected webcam, it uses it and sets the autofocus mode.

4.1.2. Vein Visualization Enhancement

In our setting, raw videos that come directly from the NIR camera provide good visualization of the vein's structure and their pattern. However, they contain some fuzzy and noisy areas caused by shades or hairs.

Veins visualization can be enhanced more using image processing or machine learning. Videos received by a camera are made up from a succession of still frames and are then played one after the other several times a second. Image enhancement algorithms can be applied on each frame separately each time a new frame arrives from the camera. The result is then displayed in the real time on the screen.

Machine Learning

The term machine learning refers to the automated detection of meaningful patterns in data [34]. Using machine learning algorithms can be beneficial in automatically recognizing veins and highlighting or colouring them, and thus, making the task even easier for the operator. An algorithm is trained on a dataset of different images in a similar or same setting as in the practical case. It "learns" then how a vein could look like and can extract it from a new given image. The task of finding a vein in an image using machine learning is not hard and totally feasible as much more complex tasks are accomplished in this field like face localization [6] and active object localization [11] and they give great results and performance. However, using machine learning requires access to a reasonably big dataset to train the algorithm, which means an images dataset, where each image is taken in the same or similar setting as our setting. Such dataset is unfortunately unavailable. Moreover, if the image provides good contrast of the veins pattern, there is no need for such automatic recognition because it will be then an easy task for the operator to visually recognize it. For these reasons, machine learning was not employed in this work.

Image Processing: General Overview

Image processing includes computational operations such as editing, analysing, enhancing and reconstructing images. The meaning of the term image processing is not defined precisely. In the narrow meaning, image processing concerns operations that transform an image to another one. In the broader meaning, image processing includes all operations that have information at the visual output or input like image analysis, pattern recognition or Image synthesis.

The focus is image processing as image transformation. Raw images are received by the camera and then transformed into another images in order to enhance vein's contrast.

Many image processing algorithms were tested in this work. But only one approach was followed and used, the adaptive image thresholding, which will be explained in detail in application work modes section. In the following, we discuss some of image processing algorithms, which we tried to employ in this project, but yielded insufficient results.

Image Processing: Hough Transformation

The Hough Transform is a method for finding lines in an image. In its classical form it was restricted to features that can be specified in a parametric form. However, a generalized version of the algorithm exists which can also be applied to features with no simple analytic form [22]. Before applying Hough transform, an edge detector like Canny edge detector must be applied. Using Hough transform, lines in the image can be detected. The idea depends on the fact that after edge detection, only a few lines that pass through a given set of edge pixels exist. These common lines can be thought of as candidates for the actual line (if it exists) that passes through all of the nearby edge pixels. To find this common set of lines, a Hough transform to Hough space is performed.

To understand the Hough transform, it is important to know what the Hough space is. Each edge pixel in the original space is a line or curve in the Hough space. In Hough Space, each line represents a point from the original space, and each point represents a line from Image Space. The problem is now to solve for the intersections between lines in Hough space, and transform that intersection point back into the original space to obtain a line which intersects enough edge pixels. Using Hough transform method has shown promising results on outer edge detection. However, practically and probably due to erroneous calibration of algorithm variables, line detection by Hough transformation using OpenCV yielded insufficient results.

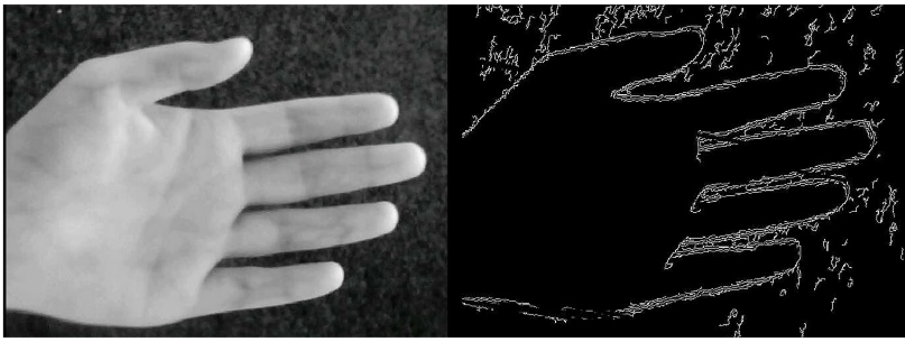

Figure 4.1.: Hough transform, detection of edges

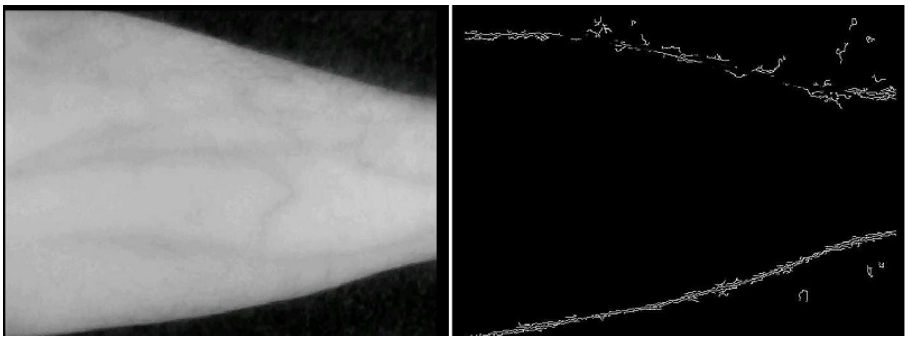

Figure 4.2.: Hough transform, failed detection of veins

Image Processing: Laplacian Transformation

The Laplacian of an image highlights regions of rapid intensity change and is therefore often used for edge detection. It can be considered as an equivalent measure of the second derivative in 2D. Given f, a function of time, with value $f(t)$ at time t, the Laplace transform of f is denoted $\widetilde{f}$ and it gives an average value of f taken over all positive values of t such that the value $\widetilde{f}(s)$ represents an average of f taken over all possible time intervals of length s [18].

$$\mathcal{L}[f(t)] = \widetilde{f}(s) = \int_0^\infty e^{-st} f(t) dt, s > 0 \tag{4.1}$$

The idea behind the Laplacian transformation is simple. If the change in a pixel in the second derivative is steep enough, it is marked as an edge pixel. Deciding that is done by calculating the zero crossings and that is when the slope changes direction from positive to negative or vice versa. That point is then the edge's location.

Similar to the Hough transformation, the Laplacian transformation yielded insufficient results in detecting veins.

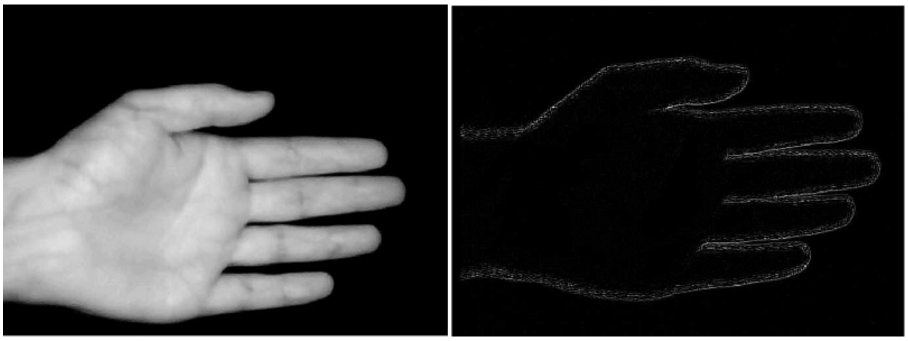

Figure 4.3.: Laplace transform, detection of edges

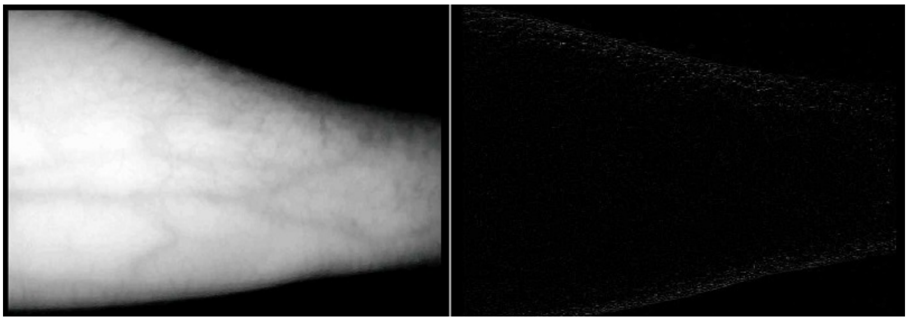

Figure 4.4.: Laplace transform, failed detection of veins

4.2. Application Work Modes

From software point of view, the application can work under two modes: raw NIR images without image processing and adaptive thresholding.

4.2.1. Raw NIR Images Mode

The term "raw NIR images" refers to the fact that no image processing operation was performed on the images before showing them on the screen. As stated in previous chapters, images from the adjusted webcam are sent to the mobile device via a third-party library, the UVC Camera library. As the camera is adjusted, it can sense almost only NIR light and no visible light. These raw images are not purely raw from hardware point of view, as they are already manipulated through the NIR-pass filter. They appear to be transformed in the greyscale. For normal healthy patients with relatively light skin colour, showing raw NIR images can provide good visualization of the veins pattern. Figure 4.5 shows an NIR image of the arm of a normal healthy male person. No tourniquet was used while taking these images.

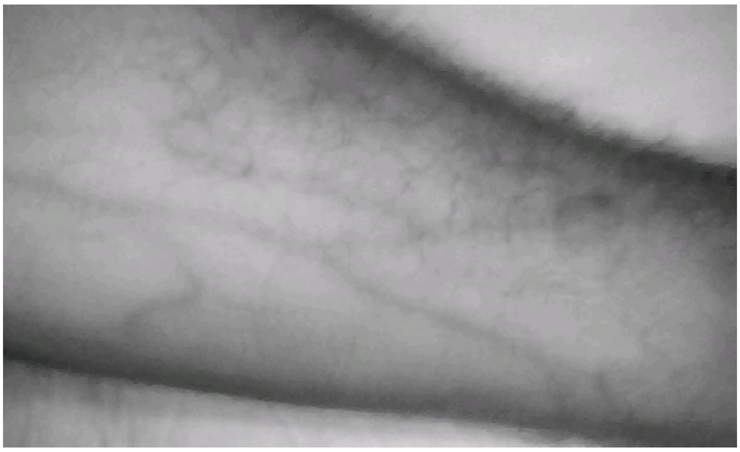

Figure 4.5.: Raw NIR image of the arm of a normal healthy male person.

The Figure 4.5 shows a good contrast of the vein on the arm. Localizing the vein depending on this image is then an easy task. However, raw NIR images don't always show such good contrast without any processing. Many different factors could be responsible for poor contrast in raw NIR images such as body weight, skin colour and gender. In the Figure 4.6 shows an arm of a normal female person on the same setting, poor contrast is noticeable and the vein has barely darker colour than the surrounding area. The result of venepuncture depending on images with such veins contrast will not be better than the traditional way of visual examination and palpation. The only remarkable difference between the two persons here is the gender. However, the gender factor is not necessarily the deciding factor. For another female person, vein contrast was as good as the contrast in Figure 4.5.

Figure 4.6.: Raw NIR image of the arm of a normal healthy female person.

4.2.2. Adaptive Thresholding Mode

Because of poor vein contrast of raw NIR images in some cases, image processing can be of great benefit. Adaptive thresholding has given very good results in terms of performance and vein contrast.

Image Segmentation

Image segmentation is a fundamental process in many image, video, and computer vision applications. It is often used to partition an image into separate regions, which ideally correspond to different real-world objects [29]. It is the process of assigning a meaningful label to every set of pixels in the image so that these sets represent different segments. Like separating an object from the background or segmentation of multiple different objects in an image. Image segmentation is usually performed by identifying common properties between regions. Or, similarly, by identifying differences between them.

Image Thresholding

Image thresholding is the most common and simplest image processing approach to segment images. In general image thresholding aims to change pixel values depending on a threshold. For images in the greyscale, image thresholding yields binarized images, i.e. images that only has two colours.

Let $f(x;y)$ be the grey value of the image at pixel in position $(x;y)$; then thresholding using threshold value t transforms this image into a binary image $f'(x;y)$ as follows:

$$f'(x;y) \begin{cases} 0 & \text{if } f(x;y) \leq t \\ 255 & \text{otherwise} \end{cases} \tag{4.2}$$

All pixels below the threshold t are turned into 0 and all others that are above this threshold are turned into 255. The threshold as well as the two assigned pixel values can be adjusted based on application specification.

Global Threshold

Global thresholding approach can be used if the intensity distribution between the segments is very distinct. In this method, only a single value (global value) for the threshold for all pixels in the image is used. Threshold value should be then carefully selected and based on practical results. However, any changes in the lightning conditions or colours of the image could affect the thresholding drastically and misclassify big regions in the image. Because the dependence is on the colour intensity only, not on any relationships between the pixels. These effects get worse as the noise increases, because it's more likely that a pixel's intensity doesn't represent the normal intensity in the region. Applying global thresholding on the NIR images has given very bad results. Figure 4.7 shows a global thresholding result on the image in Figure 4.5 using threshold value of 160.

Figure 4.7.: Global thresholding on the image in Figure 4.5; threshold value: 160

Local (Adaptive) Threshold

Another problem with global thresholding is that changes in illumination across the image may cause parts to be brighter and others darker. To overcome the global thresholding shortcomings, adaptive thresholding can be used. Unlike global image thresholding, local image thresholding uses multiple, local, thresholds for each region of the image. Finding the local threshold across the image regions depends on the fact that smaller image regions are more likely to have approximately uniform illumination, thus being more suitable for thresholding. Automatic calculation of local threshold for each pixel can be achieved in many approaches such as mean calculation and Gaussian methods. In both methods, the threshold is calculated for each pixel by taking the neighbouring pixels into consideration. Depending on their values, the threshold value of the pixel can then be decided.

Local Threshold Calculation by Mean

For each pixel at $(x;y)$, the threshold value $T(x;y)$ is the mean value of the neighbouring pixels of $(x;y)$ in an area of size $blockSize \times blockSize$ minus a correction constant C.

Increasement of the block size results in more neighbouring pixels taken into consideration while calculating the threshold value for each pixel. Determining the block size is deciding factor for the quality of the results. Luckily, the block size can be set based on visual assessments of the results and doesn't need to be reconsidered for other images in the same setting.

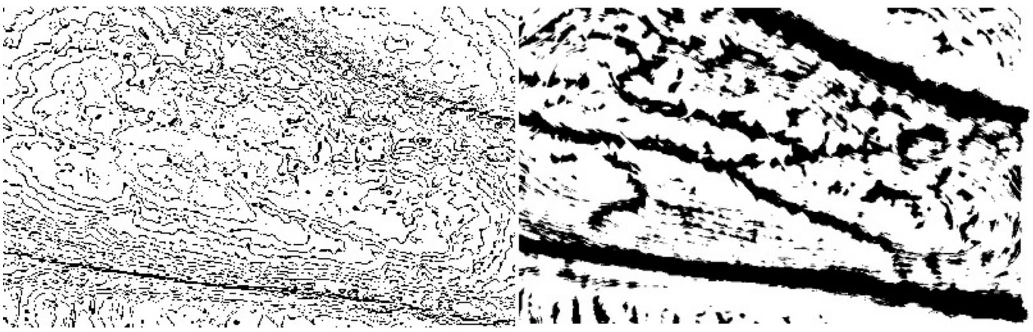

Figure 4.8.: Effect of block size on mean adaptive thresholding;
C of both: 2; block size: left 7, right 41

The correction constant is a constant value that is subtracted from each threshold. Increasing this constant reduces noise but, of course, might result into loss of some desired details. Normally, this constant is positive, but it can be assigned a negative value as well.

Figure 4.9.: Effect of correction constant on mean adaptive thresholding; block size for both: 91; C: left 0, right 2; Partial loss of details is noticeable

Local Threshold Calculation by Gaussian

For each pixel at $(x; y)$, the threshold value $T(x; y)$ is the is a weighted sum (cross-correlation with a Gaussian window) of the neighbouring pixels of $(x; y)$ in an area of size $blockSize \times blockSize$ minus a correction constant C.

The main approach is similar to the previous approach in mean calculation. The only difference is the relation between the pixels or pixel regions. In mean calculation approach, all pixels in a surrounding area of size $blockSize \times blockSize$ have the same weight in the calculation, and thus, they have the same effect on the final threshold value. In Gaussian calculation approach, cross correlation of the area surrounding each pixel is used to assess how similar this area with each neighbouring area. A weighted sum is then calculated.

Cross-Correlation $g(i; j)$ of two functions $f(x; y)$ and $h(x; y)$ can be calculated as follows:

$$g(i; j) = f(x; y) \otimes h(x; y) = \iint_{-\infty}^{+\infty} f(x; y)h(i - x; i - y)dxdy \tag{4.3}$$

Similar to mean adaptive thresholding, block size and correction constant have impact on the result's quality.

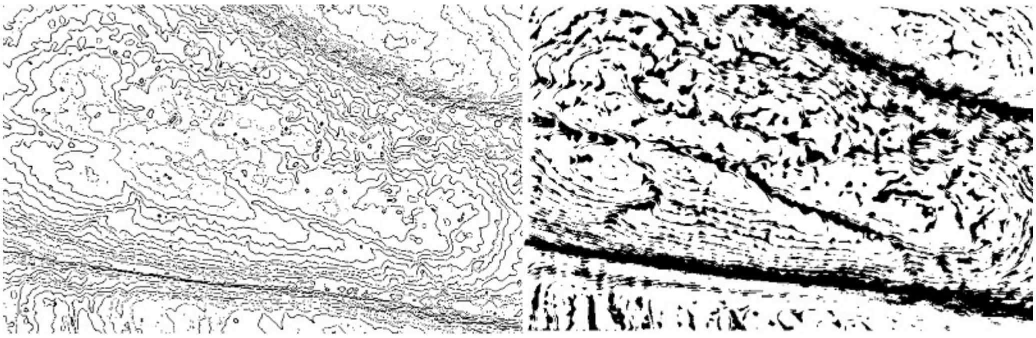

Figure 4.10.: Effect of block size on Gaussian adaptive thresholding; C for both: 2; block size: left 7, right 41

Figure 4.11.: Effect of correction constant on Gaussian adaptive thresholding; block size for both: 91; C: left 0, right 2

Median Filter

In addition to the correction constant, image noise removal can be achieved by applying a filer after getting the adapt thresholding result. A good candidate here is the median filter. Similar to the adapt thresholding, median filter is a nonlinear image processing operation. The median filter is an effective method that can, distinguish out-of-range isolated noise from legitimate image features such as edges and lines. Noise reduction is done replacing each pixel with the median of all pixels in a defined size neighbourhood w of the given pixel.

$$f(x;y) = median\{g(x;y)|(x;y) \in w\} \tag{4.4}$$

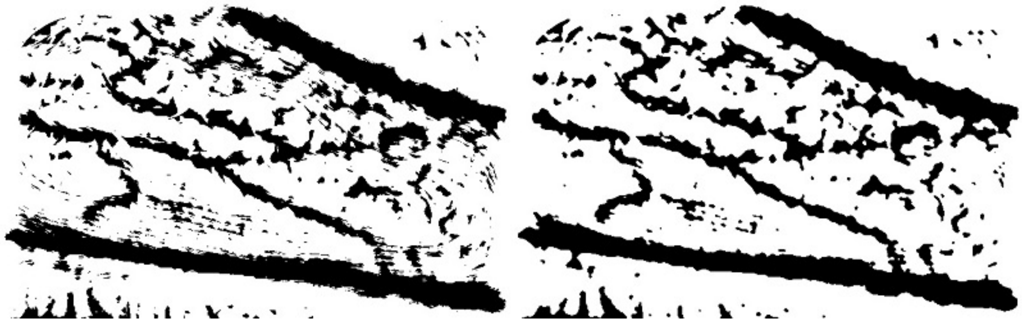

Figure 4.12.: Median filter; left: result of Gaussian adaptive thresholding with block size: 91, C: 2; right: result of applying median filter with kernel size: 4; Noise is reduced with no details loss

Moreover, the median filter is better than the average filter, which calculates the average of pixels in the neighbourhood and replaces every pixel with it. Because in average filter, a single pixel with a very unrepresentative value can significantly affect the average value of all the pixels in its neighbourhood.

4.3. Application Structure

The software application is basically an android application composed of two layers: the native layer, written in C++ and the Java layer. The Java layer includes user interface (UI) components of the application and all application business logic. The C++ layer is responsible for communicating with the camera as well as for image processing of raw images coming from the camera using open computer vision library (OpenCV).

Because compiled Java code runs on the Java virtual machine (JVM) which is a part of the Java runtime environment (JRE). Whereas compiled C++ runs directly on the operating system (OS), a bridging component Between the two layers is needed. The Java native interface (JNI) allows the two layers to interact with each other. It is a Java feature that allows Java code to call native applications and libraries written in languages such as C, C++ and Objective-C.

The Figure 4.13 below shows the application high-level architecture.

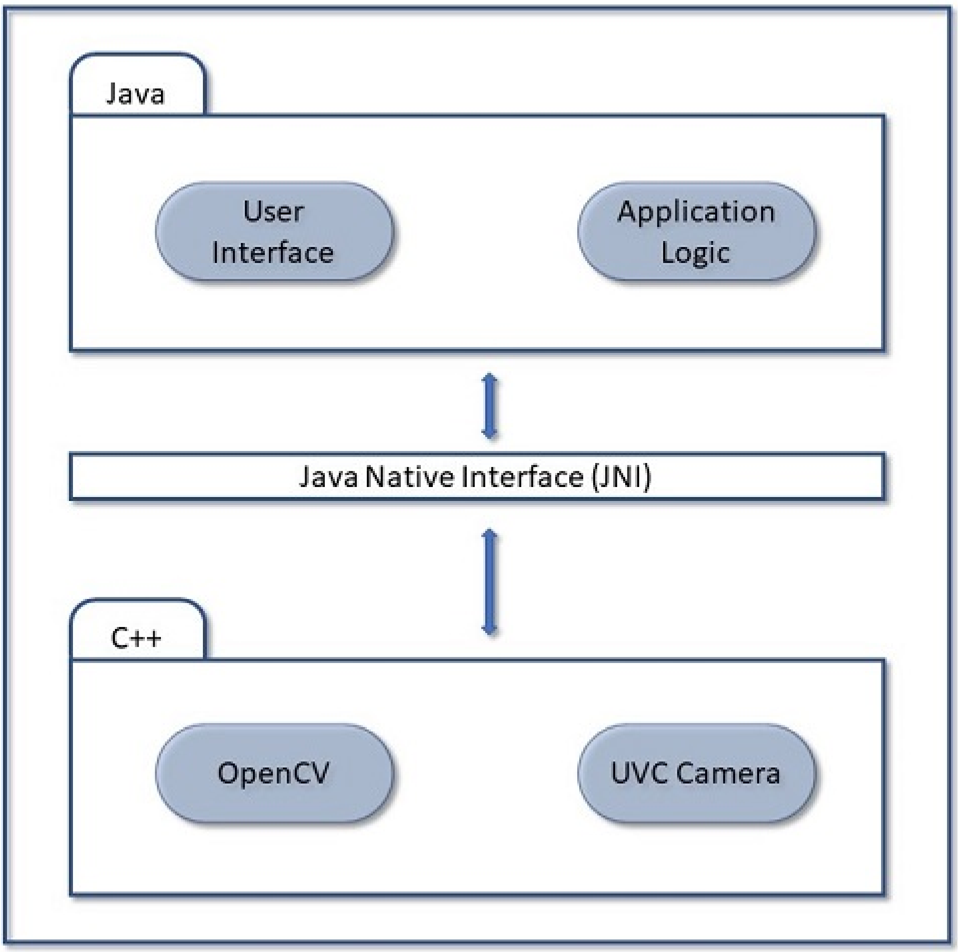

Figure 4.13.: Application architecture

4.3.1. C++ Layer

Using native C++ has many benefits in terms of high performance and compatibility. C++ is a highly flexible and adaptable language. Since its creation, it has been used for a wide variety of programs including firmware for micro-controllers, operating systems, applications, and graphics programming [31].

Android offers a good and easy-to-use C++ Integration via the JNI. In fact, Android Studio (current version 3.2.1) offers an option to include C/C++ support when creating a new application. Native C++ classes as well as corresponding JNI methods and Java classes are automatically created. Even for an existing project, importing a native C++ library or adding C++ code can be done easily on Android Studio.

One big advantage of using C++ is the cross-platform feature which the language offers. Code can be written on any environment and seamlessly run on other environment. During development, it was very inconvenient to run and test directly on a mobile device. Because of time loss in building the android application, packaging it and installing the APK file on the device. Instead, development, algorithms calibration and tests were performed directly on Linux using a desktop and the CLion IDE.

Written in C++, this application layer encompasses the UVC Camera library which allows the application to communicate with the camera as well as the native image processing module, the OpenCV module.

USB Video Class

USB Video Class (UVC) describes the capabilities and characteristics of video streaming devices. It is widely used, such as desktop video cameras or webcams, digital camcorders, still-image cameras, and so forth. USB Video Class (UVC) is a standard class specification that standardizes video streaming functionality on the USB. It enables devices like webcams, digital camcorders, analogue video converters, analogue and digital television tuners etc to connect seamlessly with host machines. UVC supports streaming multiple video formats and provides structures for describing the functionalities of the video device to the host and defines USB requests to control different parameters of the device and characteristics of the video stream. It also provides flexibility for a video device to support multiple video resolutions, formats and frame rates, which highly influences the bandwidth negotiation between the device and the host [39].

UVC Camera Library for Android

Many OS platforms have native support for UVC drivers which greatly reduces the time required for developers to connect UVC devices. Unfortunately, android doesn't offer such a support, therefore, to connect a UVC device such as a webcam, the device driver must be written by the developer. Nevertheless, third-party and open source libraries offer good alternative solution for the UVC device drivers. An open source library to access to UVC webcams on non-rooted Android device called UVCCamera was used in this project [37]. The library works on minimum android version 3.1 or later (API >= 12), but Android 4.0(API >= 14) or later is recommended. Of course, to use it, many configurations and tuning steps were needed. Especially, due to the fact that no enough documentation is available.

Open Computer Vision Library

OpenCV is written in C and C++ and runs under Linux, Windows and Mac OS X. OpenCV was designed for computational efficiency and with a strong focus on realtime applications and can take advantage of multicore processors. One of OpenCV's goals is to provide a simple-to-use computer vision infrastructure that helps people build fairly sophisticated vision applications quickly [9].

OpenCV offers support for common image processing algorithms. Adaptive thresholding, for example, is implemented in this project using OpenCV. The video captured by the camera is a sequence of images. Each image can be represented as a matrix of numbers. Image processing algorithms tend to be quite computationally heavy, therefore, OpenCV has its own type to represent arrays, namely the *Mat* class. *Mat* can be used to store real or complex-valued vectors and matrices, grayscale or colour images and more. It is optimized to be passed to the functions without making unnecessary copies. Each *Mat* object has a header, the matrix that holds the data may be shared between two instances of them by having their matrix pointers point to the same address. Moreover, the copy operators will only copy the headers and the pointer to the large matrix, not the data itself [38].

Android NDK

The Android NDK is a companion toolset for the Android Software Development Kit (SDK), designed to augment the Android SDK to allow implementation of performance-critical portions of android applications using machine code-generating programming languages like C, C++, and assembly [16] or to access physical device components, such as sensors and touch input. The NDK builds the native shared libraries, or *.so* files, from C/C++ source code as well as the native static libraries, or *.a* files, which can be linked into other libraries.

4.3.2. Java Layer

The Java layer includes the user interface (UI) components and all application business logic. The compiled Java code along with any data and resource files required by the application is bundled by the android asset packaging tool (AAPT) tool into an android package, an archive file marked by an .apk suffix.

While the core functions in the UVC Camera library are written in C/C++, the library offers a Java interface and it has many modules written in Java. Therefore, here, the Java layer, additionally to the application itself, addresses some of the library parts that are written in Java and used in the application.

Permissions: USB Host

By default, Android does not allow an application to access the devices connected to the USB port. To enable an application to interact with a the UVC camera directly connected by OTG cable, this functionality must be declared by adding the `<uses-feature android:name="android.hardware.usb.host"/>` tag in the manifest section in `AndroidManifest.xml`.

USBMonitor

This class manages the USB connection via the OTG port on the android device. It notifies the application when a USB device is attached, detached, connected or disconnected. Principally, the USB, and, therefore, the OTG, protocol allows connection of multiple peripherals. Of course, a USB hub is then needed. The USBMonitor class provides the application with a list of connected devices as well as each device's vendor ID, product ID, device class and subclass, device protocol and more hardware-related information.

Permissions: Open GL

OpenGL ES (Open Graphics Library for Embedded Systems) is an API to graphics hardware. The API consists of a set of several hundred procedures and functions that allow a programmer to specify the shader programs, objects and operations involved in producing high-quality graphical images, specifically color images of three-dimensional objects [24]. Android includes support for high performance 2D and 3D graphics with the OpenGL ES. Similar to USB host permission, adding `<uses-feature android:glEsVersion="0x00030000"/>` tag to include OpenGL ES support is needed. This tells android to expect the version 3 of OpenGL ES.

ImageProcessor

The image processor class is part of the OpenCV Java-wrapper. It offers frame-based image processing capabilities using OpenCV. After configured and set up, whenever a frame arrives from the camera to the UVC Camera module, the corresponding activity calls the *doProcess* method in the image processor class. The image processor Java class calls another C++ image processor class via the JNI. The later receives an image then by reference, processes it and sends it back to the Java side. After that, the Java image processor callback *onResult* is called to return the processed frame to the activity. The fast succession of frames (about 30 fps) makes up the processed video.

Android SurfaceView

After the frame has been processed in the image processor class, it is then sent back to the application to show it on the screen. Drawing on Android activities is performed by the same UI thread which is also used for all user interaction. Therefore, using this thread to draw the processed, or even raw, frames is not feasible and will cause the application to freeze. Instead, android offers another view type, the SurfaceView, which can be drawn on a background thread without affecting the user experience. Therefore, results are drawn on a SurfaceView. However, SurfaceViews have some limitations. The main limitation is that they are not hardware accelerated, while most of operations on normal Views are hardware accelerated using OpenGL ES. Another limitation is that, SurfaceViews have dedicate surface buffer while all Views share one surface buffer. In another words, SurfaceViews cost more resources. Despite its limitations, practically, SurfaceView is sufficient for this project goals due to the small frame size and low resolution.

Control of Algorithm Type and its Parameters

The application offers simple UI components to control the image processing algorithm type or its parameters. For example, as explained earlier, adaptive thresholding can be applied with or without the median filter. Selection of this option is done in the Java side through UI components and then sent to the C++ side via the JNI. Similarly, algorithm parameters can be changed the same way. A slider to adjust the kernel size of the median filter is shown on the screen. The kernel size is stored as a local variable in the C++ image processor class. During every image processing operation, i.e. on every frame, this variable is read and then used by the algorithm. When the user changes the slider's value, the android activity calls a method in the Java image processor to change the kernel size, which in turn calls a corresponding method in the C++ image processor. Finally, the value is changed in that class and stored there. Java stores no information about the algorithm type or parameters and they are queried from the C++ side whenever they are needed.

5. Results and Discussion

5.1. Results

In this section, results of the proposed solution on people with different skin conditions and properties are explored and discussed.

5.1.1. Results on Tattooed Skin

Tattoos can limit the visual access to the vein, which plays an important role in the venepuncture operation. Usually, operators are limited to palpation when trying to find a vein on a heavily tattooed skin. Pigments of the tattoos are lodged in the dermis. NIR imaging tools can be beneficial in visualizing the veins through the tattoo pigments. Two main factors can affect the penetration ability of NIR light through tattoo pigments to the veins: ink colour and density. The literature in this area is limited to tattoo removal by light beam or laser. However, a study on revealing cover-up tattoos to identify the underlying older tattoos [10], can be a good source of information in this domain too. While, in this study another factor of identification quality was taken into consideration, which is the tattoo age, we will discuss only ink colour and density as age of the tattoo affects mainly the density and partly the colour.

Dye Density

Density affects the veins NIR visualization when dye colours appear more saturated in the infrared image. Density of a colour dye increases when mixed with black. For example, in Figure 5.1 [10], where although the tattoo ink colour is green, normally a dye colour that is almost invisible in the NIR region, the regions where green is mixed with black are visible in the NIR image and can block the veins NIR visualization.

Figure 5.1.: Density comparison between a visible light image and an NIR one of a tattooed skin. Low density regions in some colours like green, red and orange are partly invisible in the NIR image. Regions where green is mixed with black are visible.

Dye Colour

Ink colour is even more important than density, as some colours absorb more NIR light than others and a very thin layer of pigments can absorb most of the projected NIR light and, thus, prevent it to reach to the underlying veins. In Figure 5.2 [10], dye density in the visible range is clearly intense. However, in the NIR range, tattoo is totally invisible because the used colours (red, yellow and orange) don't absorb NIR light. Merely traces of the tattoo shape are visible in the NIR range. This is caused by the depigmentation of the underlying skin following healing of the skin after the tattoo [10] and has nothing to do with the tattoo itself or its colours.

Figure 5.2.: Colour comparison between a visible light image and an NIR one of a tattooed skin.

Conclusion

Tattoos can limit the visual examination of the veins when intense. NIR imaging can sometimes penetrate the tattoo pigments and let the operators see through them. Depending on the ink colour and intensity, NIR light can either be absorbed directly in the dermis by the tattoo pigments and behave just like the visible light or penetrate them to get absorbed then by the haemoglobin in the veins and results in good visualization of the veins. The Table 5.1 [10] shows a brief summary of the effects of ink colour and density on the success of NIR visualization on a tattooed skin.

Property	Successful visualization	Unsuccessful visualization
Dye colour	Yellow, red, green, blue and light purple	Black and dark purple
Dye density	Light and pale tattoos	Colour inks mixed with black. The more black the less visible.

Table 5.1.: Effect of dye colour and density on the success of NIR imaging on a tattooed skin

5.1.2. Results on Different Skin Colours

Skin colour plays a role in the NIR light visualization skin. The element that gives the skin its colour is melanin. The more melanin in the skin, the darker it is. As stated in the first chapter, absorption of epidermis in the NIR spectral range is defined almost exclusively by its melanin. That means, theoretically, darker skin types absorb more NIR light and, therefore, less light is transmitted to the dermis and the veins.

Fitzpatrick Skin Phototype

The Fitzpatrick skin phototype classifies the skin types into six levels, shown in Table 5.2, depending on the amount of melanin pigment in the skin. The melanin amounts determine the skin colour as well as the likelihood of burning.

Skin Type	Colour	Description
Type I	Pale white skin	Extremely sensitive skin, always burns, never tans
Type II	White skin	Very sensitive skin, burns easily, tans minimally
Type III	Light brown skin	Sensitive skin, sometimes burns, slowly tans to light brown
Type IV	Moderate brown skin	Mildly sensitive, burns minimally, always tans to moderate brown
Type V	Dark brown skin	Resistant skin, rarely burns, tans well
Type VI	Deeply pigmented dark brown to black skin	Very resistant skin, never burns, deeply pigmented

Table 5.2.: The Fitzpatrick skin phototype

Melanin Rate Effect

Melanin can affect the NIR imaging indeed, but the difference in melanin rates between different human skin colours doesn't play a major role in light absorption and scattering properties in the NIR range [27].

Conclusion

Despite the high melanin rate in darker skins, skin colour doesn't limit the NIR vein visualization. A quick comparison between the results on skin of type VI and another of type II is performed. Both persons participated in this comparison are males and have close age and body weight. The Figure 5.3 shows a row NIR image as well as the result after applying adaptive thresholding on a skin of type VI. Veins are good visualized in both images despite the high melanin rate. Figure 5.3 also shows two images in the same setting as in Figure 5.3, but the skin type is II, which is brighter than the type VI.

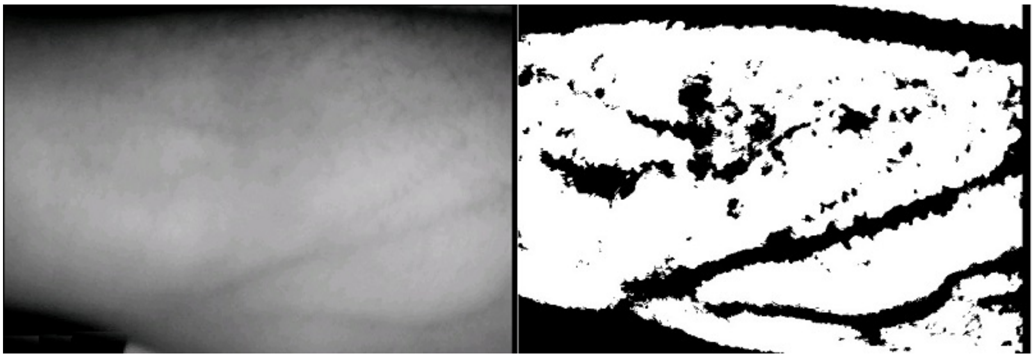

Figure 5.3.: Row NIR image and the result of adaptive thresholding on a skin of type VI. Veins are good visualized despite the high melanin rate

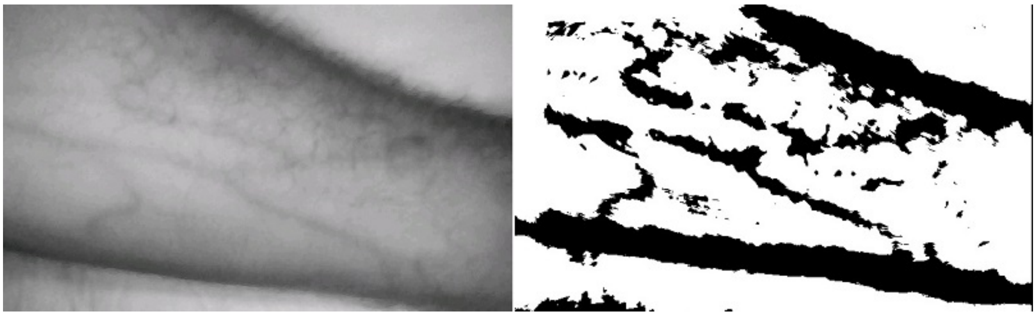

Figure 5.4.: Row NIR image and the result of adaptive thresholding on a skin of type II. Veins are good visualized

5.1.3. Results on Skin with Diseases

Although most of skin diseases don't limit the venepuncture procedure, some skin diseases can be a real suffering for patients. It is sometimes near to impossible to locate the vein just by visual examination and palpation.

Scleroderma

Scleroderma is a chronic autoimmune disorder characterized by the hardening of connective tissue, internally and externally. The initial symptom for both forms is usually the hardening and tightening of the skin. In its advanced stages, skin, and skin of the arms, can be as hard as the skin on the heels.

Scleroderma: Clinical Study

We performed a study on a 56 years old female patient with advanced scleroderma. Regular clinical treatments of this disease often require an intravenous access. However, obtaining this access is near to impossible without any imaging devices. The Figure 5.5 shows a visible range image of her arm. No veins can be located visually in the image and a needle mark of a failed venepuncture attempt is visible. 3-5 failed attempts to obtain the intravenous access have been recorded each time a clinical treatment is required. Important treatments have been cancelled because operators and even doctors at university hospitals were unable to perform the venepuncture operation. The suggested solution was to implant a permanent device. A port in the chest that is connected directly to the heart. This implantation operation is usually recommended to scleroderma patients in middle to advanced stages.

Figure 5.5.: Visible range image of a scleroderma patient arm skin. Skin is extremely hardened. Veins cannot be located visually

Scleroderma: Ultrasound Vein Imaging

Practically, using ultrasound imaging with colour Doppler has increased the venepuncture success rate to 100%. Nevertheless, as mentioned in the first chapter, it requires well understanding of the Doppler image generation, high hand-eye-coordination skill and, of course, the availability of the device itself.

Scleroderma: Results

The Figure 5.6 shows results of the proposed solution on the arm of the given scleroderma patient. Veins can be seen in the raw NIR image, but they appear to be clearer and with more contrast in the processed one.

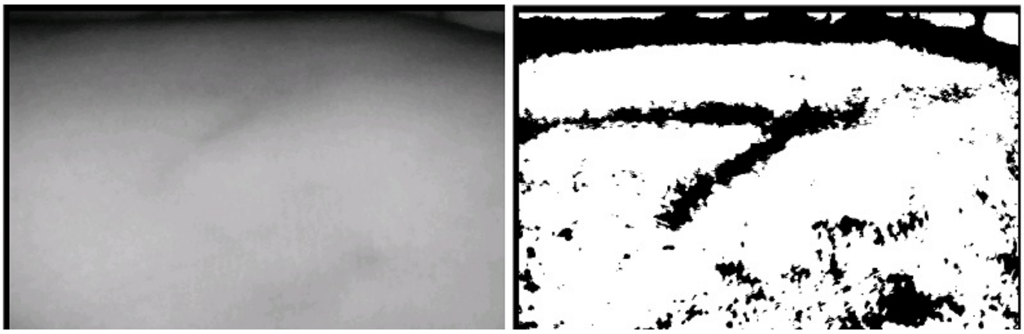

Figure 5.6.: NIR image and the result of applying adaptive thresholding on a scleroderma patient. Veins are visualized

5.2. Conclusion

In their different forms, medical imaging techniques have become an essential part of any clinical operation. Peripheral veins imaging technologies are gradually getting more attention and investment, but they are expensive, and their availability is limited to very special clinics. We proposed a lost-cost mobile vein viewing system, utilizing near infrared light and a simple digital camera. The focus is to develop a viewing system of the pattern of peripheral veins, but optimized to make the venepuncture operation easier. The prototype has shown promising results in terms of vein visualization and ease-of-use on different skin types and conditions.

5.3. Future Work and Possible Application Areas

Further research in mobile vein viewing approaches can go in many different directions such as machine learning or using another technology such as Ultrasound. Applications for the proposed solution can take place also in many different areas related to vein imaging.

5.3.1. Hybrid Technology, NIR + US

Ultrasound imaging devices has become more mobile and cheaper. Initially, at the begging of this work, we faced the decision of using either NIR or US imaging. We chose NIR due to their high availability, low cost and ease-of-use. US imaging, as stated earlier, has many features such as vein depth estimation. But using US devices in this field, however, is limited because of their big size and high cost. Luckily, since 2009, researchers at Washington University have developed a line of low-cost ultrasound probes that run on small PCs and mobile devices.

A hybrid method that utilizes both NIR and US technologies using a smartphone can be a good candidate for further research. Automatic comparison between the NIR and US images can provide information about vein location, depth and status. The software has to understand and analyse both images to extract such information.

5.3.2. Burns Assessment

Evaluation of the surface and the depth of skin burn is essential, as such evaluation enables the appropriate choice of treatment. Clinical assessment is currently the most frequently applied method in burn depth evaluation. It is, however, error-prone and not accurate. Using NIR imaging can provide more information about the burn severity and depth [1].

5.3.3. Skin Abnormalities Recognition

Many skin abnormalities can be examined visually, however, some diseases, like cancer, are hard to be detected visually. Skin cancer is the most common human cancer. The clinical diagnosis is often difficult as many benign skin lesions resemble malignancies upon visual examination, thus analysis of skin biopsies remains the standard diagnosis. A rapid, non-invasive technique that could be utilized for characterization of skin lesions prior to biopsy would be useful [26]. LEDs with different wavelengths can be utilized and controlled through a control circuit. Application then measures and compares different records in different wavelengths.

Appendices

A. Compatible Devices

List of some UVC-compatible devices: [12]

Manufacture	Model	Product Name	Android OS
ASUS	Nexus7	Nexus7	4.1.2
ASUS	Nexus7	Nexus7	4.4.2
Acer	Iconia One7	B1-730HD	4.3
Google	Pixel	Pixel	7.1
HTC	Htc One(m8)	One_M8	5.0.1
HTC	Nexus9	Nexus9	5.0.1
Huawei	Nexus 6P	H1512	6.0
LG	G Pro 2	LG-F350L	4.4.2
LG	G pad 2	LG-P815L	5.0.2
LG	G2	LG-F320L	4.4.2
LG	G2	LG-F320S	4.4.2
LG	G3	LG-D855	4.4.2
LG	G3	LG-F400L	4.4.2
LG	G3	LG-F400S	4.4.2
LG	G3	LG-F400S	5
LG	G5	LG-F700S	6.0.1
LG	G6	LG-G600S	7.0
LG	Gx	LG-F310L	4.4.2
LG	Nexus 5X	Nexus 5X	6.0
LG	Nexus5	Nexus5	4.4.2
LG	Optimus G Pro	LG-F240L	4.4.2
LG	V10	LG-F600S	5.1
LG	V20	LG-F800L	7.0
Motorola	Nexus6	Nexus6	5.0.1
Pantech	Vega Iron	IM-A870L	4.4.2
Pantech	Vega Iron2	IM-A910K	4.1.2
Pantech	Vega Iron2	IM-A910K	4.4.2
Pantech	Vega No6	IM-A860L	4.4.2

Pantech	Vega No6	IM-A860S	4.1.2
Pantech	Vega Popup Note	IM-A920S	4.4.2
Pantech	Vega R3	IM-A850L	4.1.2
Pantech	Vega R3	IM-A850S	4.1.2
Pantech	Vega Secret Note	IM-890L	4.4.2
Pantech	Vega Secret Note	IM-890S	4.4.2
Pantech	Vega Secret Up	IM-A900L	4.4.2
Pantech	Vega Secret Up	IM-A900S	4.4.2
Samsung	Galaxy Note 8	SM-N950	7.1.1
Samsung	Galaxy Alpha	SM-G850L	4.4.4
Samsung	Galaxy Mega	SHV-E310L	4.4.2
Samsung	Galaxy Note 1	SHV-E160L	4.1.2
Samsung	Galaxy Note 10.1	SHV-E230L	4.4.4
Samsung	Galaxy Note 2	SHV-E250L	4.4.2
Samsung	Galaxy Note 3 Neo	SM-N750L	4.3
Samsung	Galaxy Note 3	SM-N900L	4.4.2
Samsung	Galaxy Note 3	SM-N900S	4.4.2
Samsung	Galaxy Note 4	SM-N910L	4.4.4
Samsung	Galaxy Note 5	SM-N920	5.1
Samsung	Galaxy Note Edge	SM-N915L	4.4.4
Samsung	Galaxy Note 7	SM-N930S	6.0.1
Samsung	Galaxy S3	SHV-E210K	4.1.2
Samsung	Galaxy S3	SHV-E210L	4.3
Samsung	Galaxy S4	SHV-E300L	4.4.2
Samsung	Galaxy S5	SM-G900L	4.4.2
Samsung	Galaxy S5	SM-G900L	5
Samsung	Galaxy S6	SM-G9200	5.0.2
Samsung	Galaxy S7	SM-G930L	6.0.1
Samsung	Galaxy S8	SM-G950	7.0
Samsung	Galaxy S9	SM-G960N	8.0.0
Samsung	Galaxy Tab A	SM-P550	5.0.2
Samsung	Galaxy Tab S 10.5	SM-T805	4.4.2
Sony	Xperia Tablet	SGP312	4.3
Sony	Xperia Z5 premium	E6883	6.0.1

B. Incompatible Devices

List of some UVC-incompatible devices: [12]

Manufacture	Model	Product Name	Android OS
HTC	One E9+		5.0
HTC	One E9		5.0
HTC	One M9+		
HTC	Desire 626		4.4
HTC	Desire 820s dual sim		5.0
HTC	Desire 820t		
Huawei	Ascend Mate7	MT7-L09	4.4.2
Huawei	Honor 3x	G750-T00	
InFocus	M530		4.4.2
InFocus	M320		4.2.2
iocean	G7		
Lenovo	YOGA TABLET 10	B8000-H	
Lenovo	P70		
Lenovo	P780		4.2.1
Lenovo	A5000	A5000	4.4
Lenovo	A7 50 A3500	A3500-H	4.4
LG	Optimus LTE2	LG-F160L	4.1.2
LG	Optimus G	LG-F180L	4.1
Meizu	M1 metal		5.1
Meizu	MX4		4.4.2
Micromax	A240 Canvas Doodle 2	A240(A240)	4.2
Micromax	A106 Unite 2	CANVAS UNITE 2	
Prestigio	MultiPhone PAP7600 DUO	PAP7600DUO	4.2
Samsung	Galaxy S2	GT-I9100	
Sony	Xperia C5		5.0
Sony	Xperia M5 (dual)		
Xiaomi	Redmi	China(HM2013023)	4.2
Xiaomi	Redmi Note	HM NOTE 1W	4.2

Xiaomi	Redmi Note2		5.0
XOLO	Q1010i	Q1010i	4.4

C. Verified Web Cameras

List of some verified web cameras [12]

- Logitech C930e
- Logitech BCC950 ConferenceCam
- Logitech HD C615
- Logitech HD Pro C270
- Logitech HD Pro C920
- Microsoft LifeCam Studio
- Microsoft LifeCam Cinema
- Samsung SPC-A30M

List of Figures

List of Tables

Bibliography

[1] M. K. a, A. Y. b, M. C. a, B. C. b, and A. J. D. b. *Noninvasive Assessment of Burn Wound Severity Using Optical Technology: A Review of Current and Future Modalities*. Elsevier Ltd and ISBI., 2010.

[2] P. D. M. S. D. A. Anagha B. Bawase. *Infrared Hand Vein Detection System*. IOSR Journal of Electronics and Communication Engineering (IOSR-JECE), 2015.

[3] A. Andonova, N. Kim, and N. Vakrilov. *Estimation the Amount of Heat Generated by LEDs under Different Operating Conditions*. Department of Microelectronics, Technical University of Sofia, 2016.

[4] G. V. G. Baranoski and A. Krishnaswamy. *An Introduction to Light Interaction with Human Skin*. RITA, Volume XI, Numero, 2004.

[5] E. D. Baron. *Light-Based Therapies for Skin of Color*. Springer Dordrecht Heidelberg London New York, 2009.

[6] S. Behnke. *Face Localization*. University of Bonn, 2003.

[7] M. F. Benítez JM. *The Mechanical Behavior of Skin: Structures and Models for the Finite Element Analysis*. Computers and Structures, 2017.

[8] A. Bozkurtcorresponding and B. Onaral. *Safety Assessment of Near Infrared Light Emitting Diodes for Diffuse Optical Measurements*. Biomed Eng Online, 2004.

[9] G. Bradski and A. Kaehler. *Learning OpenCV*. O'Reilly Media, Inc., 2008.

[10] J. Bryson D. Wright and K. Barker. *The Identification of Tattoo Designs Under Cover-up Tattoos Using Digital Infrared Photography*. Research Group, University of Derby.

[11] J. C. Caicedo and S. Lazebnik. *Active Object Localization with Deep Reinforcement Learning*. University of Illinois and Konrad Lorenz University.

[12] *CameraFi Supported Devices*. http://www.camerafi.com/supported-devices.

[13] J. Campbell. *Intravenous Cannulation: Potential Complications*. Prof. Nurse London Engl., 1997.

[14] P. J. e. a. Carr. *Development of a Clinical Prediction Rule to Improve Peripheral Intravenous Cannulae First Attempt Success in the Emergency Department and Reduce Post Insertion Failure Rates: the Vascular Access Decisions in the Emergency Room (Vader) Study Protocol*. BMJ Open, 2016.

[15] A. I. Chen. *Image-Guided Robotics for Autonomous Venipuncture*. Rutgers, The State University of New Jersey, 2016.

[16] O. Cinar. *Pro Android C++ with the NDK*. Apress, 2012.

[17] S. DH. *Laser and LED eye hazards: Safety standards.* Optics and Photonic News, 1997.

[18] C. Dodson. *Introduction to Laplace Transforms for Engineers*. School of Mathematics, Manchester University.

[19] *Eye Safety of IREDs used in Lamp Applications, Application Note*. OSRAM Opto Semiconductors GmbH, 2016.

[20] M. Friebel and J. Helfmann. *Optical Properties of Platelets and Blood Plasma and Their Influence on the Optical Behavior of Whole Blood in the Visible to Near Infrared Wavelength Range*. J. Biomed. Opt, 2007.

[21] H. J. Galena. *Complications Occurring from Diagnostic Venipuncture*. J. Fam. Pract, 1992.

[22] A. S. Hassanein, S. Mohammad, M. Sameer, and M. E. Ragab. *A Survey on Hough Transform, Theory, Techniques and Applications*. Informatics Department, Electronics Research Institute, Egypt.

[23] N. Kourkoumelis and M. Tzaphlidou. *Eye Safety Related to Near Infrared Radiation Exposure to Biometric Devices*. Department of Medical Physics, Medical School, University of Ioannina, 2010.

[24] J. Leech. *OpenGL R ES Version 3.2*. The Khronos Group Inc., 2018.

[25] D. Mbamalu and Banerjee. *A. Methods of Obtaining Peripheral Venous Access in Difficult Situations*. Postgrad. Med. J., 1999.

[26] L. M. McIntosh, R. Summers, M. Jackson, H. H. Mantsch, J. R. Mansfield, M. Howlett, A. N. Crowson, and J. W. P. Toole. *Towards Non-Invasive Screening of Skin Lesions by NearInfrared Spectroscopy*. The Society for Investigative Dermatology, Inc, 2001.

[27] M. J. Mendenhall, A. S. Nunez, and R. K. Martin. *Human Skin Detection in the Visible and Near Infrared*. Applied Optics, 2015.

[28] R. Murphy. *USB 101: An Introduction to Universal Serial Bus 2.0*. Cypress Semiconductor Corporation, 2017.

[29] S. N and V. S. *Image Segmentation by Using Thresholding Techniques for Medical Images*. Computer Science and Engineering: An International Journal, 2016.

[30] *On-The-Go Supplement to the USB 2.0 Specification*. USB Implementers Forum, Inc. (USB-IF), 2006.

[31] S. Oualline. *Practical C++ Programming*. O'Reilly and Associates, Inc., 1995.

[32] J. A. Ramos. *Venipuncture-related Lateral Antebrachial Cutaneous Nerve Injury: What to Know?* Brazilian Journal of Anesthesiology, 2014.

[33] A. Roggan, M. Friebel, K. Dörschel, A. Hahn, and G. Müller. *Optical Properties of Circulating Human Blood in the Wavelength Range 400–2500 Nm*. Journal of Biomedical Optics, 1999.

[34] S. Shalev-Shwartz and S. Ben-David. *Understanding Machine Learning: From Theory to Algorithms*. Cambridge University Press, 2014.

[35] V. M. Shivappagoudar and B. George. *Unintentional Arterial Cannulation During Cephalic Vein Cannulation*. Indian Journal of Anaesthesia, 2013.

[36] S. C. Singh. *Basics of Light Emitting Diodes, Characterizations and Applications*. Laser Spectroscopy and Nanomaterials Laboratory Department of Physics University of Allahabad.

[37] t. saki t_saki@serenegiant.com. *UVCCamera*. https://github.com/saki4510t/UVCCamera, 2017.

[38] O. D. Team. *OpenCV 2.4.13.7 Documentation*. 2018.

[39] *USB Device Class Definition for Video Devices*. USB Implementers Forum, 2005.

[40] *Vein Detection System Using Infrared Light*. International Journal of Scientific and Engineering Research, Volume 6, Issue 12, 2015.

[41] H. W. *Risk Assesment of Light Emitting Diodes.* Journal of Laser Applications, 1999.

[42] I. Wendell T. Hill. *Electromagnetic Radiation*. WILEY-VCH Verlag GmbH and Co. KGaA, Weinheim, 2009.

[43] Yaroslavsky and P. A. N. *Optics of Blood*. V. V. Tuchin, Ed., SPIE-Press, 2002.

[44] I. T. Young, J. J. Gerbrands, and L. J. van Vliet. *Fundamentals of Image Processing*. Delft University of Technology, 2007.