



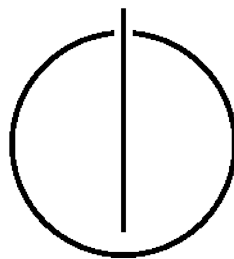
TECHNISCHE UNIVERSITÄT MÜNCHEN

DEPARTMENT OF INFORMATICS

Master's Thesis in Informatics

Vein Viewing System Using Hardware Extension Attached To Smartphones

Bakri Bitar





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Venenbeobachtungssystem mit Hardware-Erweiterung für Smartphones

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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

What is this???

Abbreviations and Acronyms

APK	Android PackAge
AAPT	Android Asset Packaging Tool
AR	Augmented Reality
EM	Electromagnetic
IR	Infrared
JRE	Java Runtime Environment
JVM	Java Virtual Machine
LED	Light Emitting Diode
NDK	Native Development Kit
NIR	Near-Infrared
OS	Operating System
OTG Cable	On The Go Cable
RBC	Red Blood Cell
US	Ultrasound
USB	Univeral Serial Bus
UVC	USB Video Class
WBC	White Blood Cell

Abstract

The goal of this thesis is to develop a low-cost noninvasive 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. Venipuncture 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.

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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, venipuncture 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 venipuncture 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% [9], [8]. The success rate can decrease below 50% in difficult populations, including pediatric, geriatric, and chronically-ill patients[16] . On average, difficult patients require three needle stick attempts per vessel, and the incidence of complications increases17 six-fold when more than three attempts are made by the same operator. Venipuncture 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 treatment11. 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 [9].

This solution utilizes a near-infrared light source to image the oxygenated hemoglobin 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 [14], [10].

Pain

Needle pain is commonly reported by patients as the worst of a 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.

Peripheral Nerve Damage

Accidental puncture of nerves is rare but can happen when the nerves are located near a vessel. 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. The best sites for venepuncture of superficial veins of the upper limbs are the median cubital vein which lies over the cubital fossa and serves as a connection between the cephalic and basilic veins. Which 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 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.

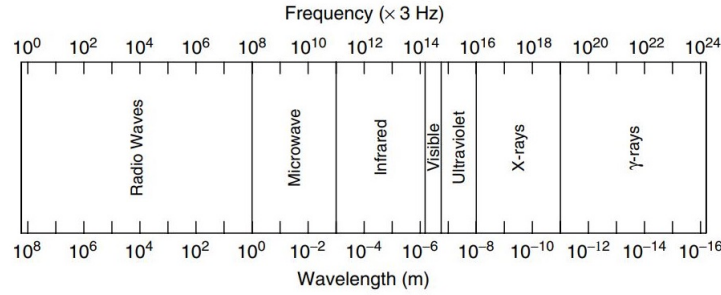


Figure 1.1.: The electromagnetic radiation spectrum.
[25]

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 [1] and [23], 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 [5].

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 analyzing 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 [4]. 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 [4].

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[4].

Absorption and scattering coefficients of skin layers are shown in figures below [4]. The graphs demonstrate that the scattering of skin layers decreases with the increasing wavelength.

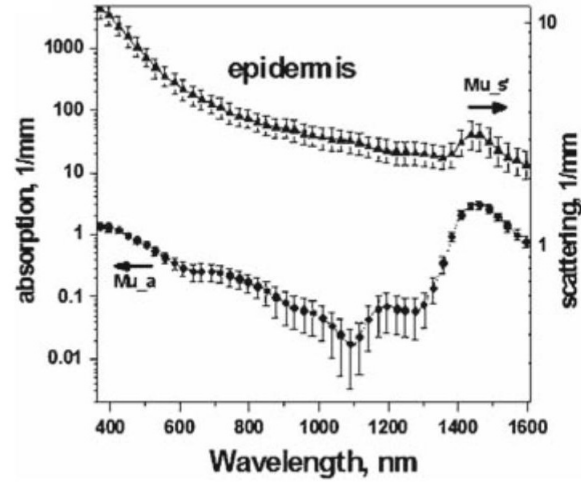


Figure 2.1.: Optical properties of epidermis, Triangles – reduced scattering coefficients, circles absorption coefficients, bars – standard errors. Averaged over 7 samples.

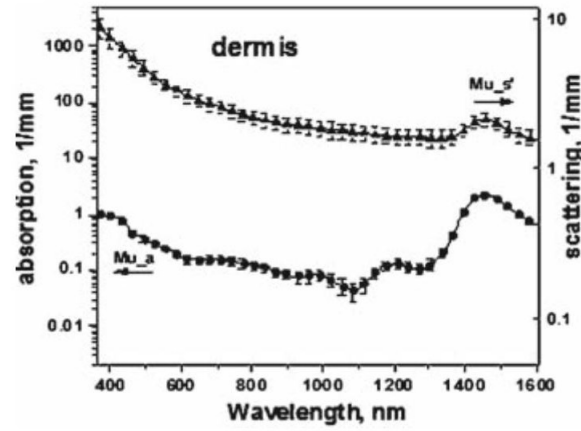


Figure 2.2.: Optical properties of dermis. Triangles – reduced scattering coefficients, circles absorption coefficients, bars – standard errors. Averaged over 8 samples.

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 [26], which account for 99% of the cellular elements [13]. The effects of the optical properties of WBCs and platelets on the light scattering and absorption by whole blood are considered negligible [26].

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

Red blood cells have a thin plasma membrane that encloses mainly a hemoglobin 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 [13]. The light scattered by a single RBC depends on its shape, volume, refractive index and orientation [13]. However the absorption of light by the RBCs is dominated by hemoglobin in its functional, oxygen-binding, forms, namely oxyhemoglobin and deoxyhemoglobin. 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.

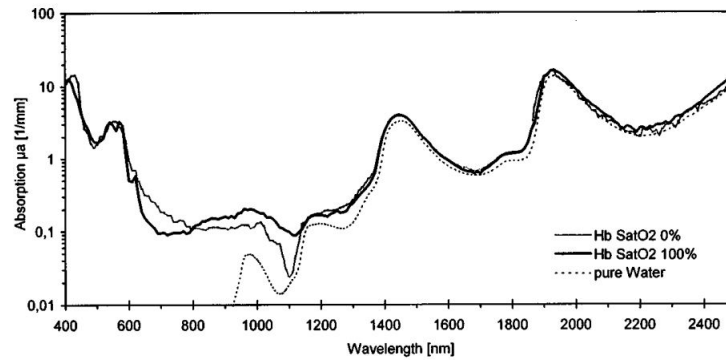


Figure 2.3.: The absorption spectrum of oxygenated and deoxygenated diluted blood.

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

3.1. Components and Design

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.

3.1.1. On-The-Go Cable

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 [18]. 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 [18].

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 [18].

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 [18].

3.1.2. Light Emitting Diodes

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)[20]. 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 [20]. 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.

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 $100\ \Omega$ 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 law as follows:

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

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.

3.1.3. 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.

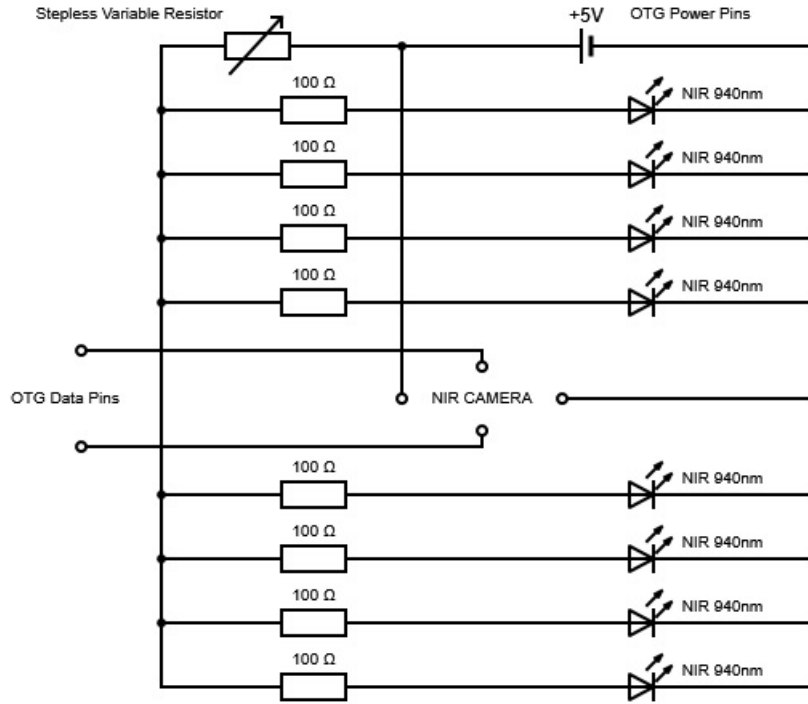


Figure 3.1.: The LEDs grid and NIR camera circuit.

3.1.4. 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 [17]. 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 [17].

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.

3.1.5. 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[15]. Safety of the NIR light should be taken into consideration from two perspectives: eye safety and skin safety.

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 [6]. 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 [6].

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 [24] [11]. 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 [12] 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.

3.1.6. Device Compatibility

Unfortunately, having an OTG port is not enough to guaranty that UVC camera will work well under Android. UVC camera 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 cameras. As no official documentation for the UVC is available.

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.

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. 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 4.1 below shows the application high-level architecture.

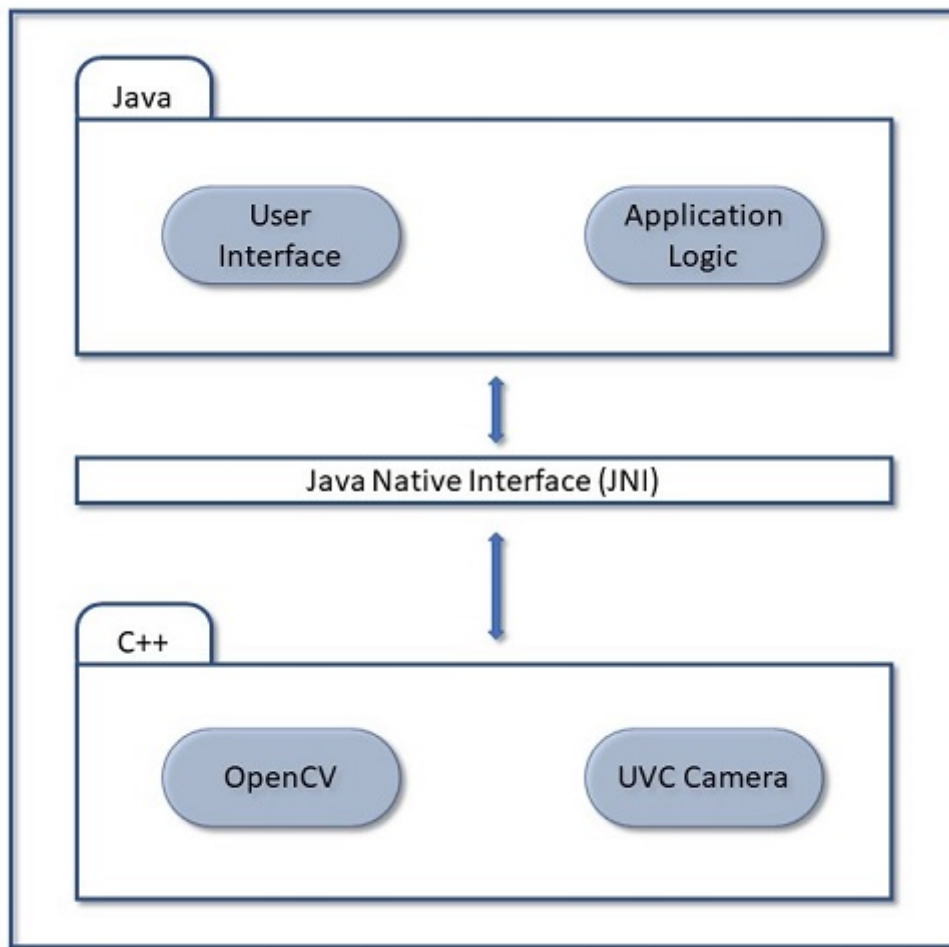


Figure 4.1.: Application architecture

4.1.1. C++ Layer

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, analog video converters, analog and digital television tuners etc to connect seamlessly with host machines. UVC supports

streaming multiple video formats including 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 [22].

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 [21]. The library works on minimum android version 3.1 or later (API ≥ 12), but Android 4.0(API ≥ 14) or later is recommended.

4.1.2. Java Layer

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. The Java layer includes the user interface (UI) components and all application business logic.

4.1.3. Permissions

USB Host

By default, Android does not allow an application to access the devices connected to the OTG port. To enable an application to interact with a the UVC camera directly connected on an OTG port, a few additional steps are required.

In `AndroidManifest.xml`, the "USB Host" functionality must be declared by adding the `<uses-feature android:name="android.hardware.usb.host"/>` tag in the manifest section.

Open GL

User Interface

Image Processing

4.1.4. Native C++ Layer

Appendices

A. Compatible Devices

List of some UVC-compatible devices: [7]

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

A. Compatible Devices

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: [7]

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

B. Incompatible Devices

Xiaomi	Redmi Note2		5.0
XOLO	Q1010i	Q1010i	4.4

C. Verfied Web Cameras

List of some verfied web cameras [7]

- 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

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