Institut für Technische Optik

Design and implementation of a low-cost pulse oximeter kit for developing- & educational purposes

Masterarbeit

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Gutachter:
Prof. Dr. Alois Herkommer

Gliederung

- Einleitung
- Grundlagen
- Konzeption
- Ergebnis
- Fazit & Ausblick

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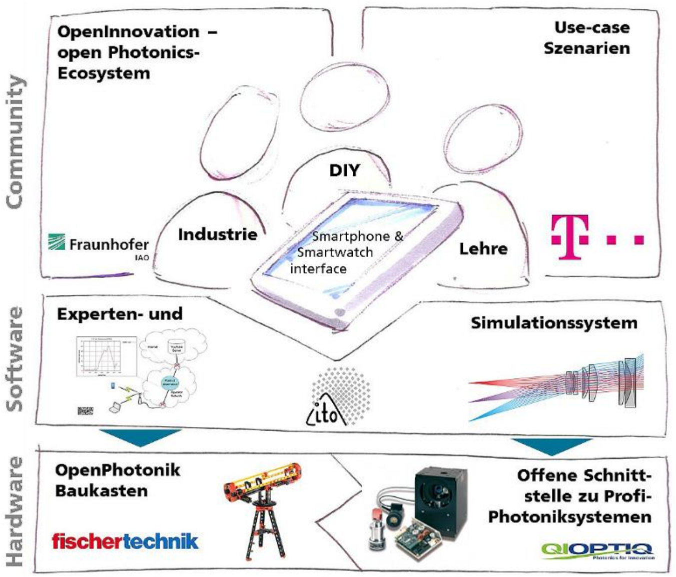
Motivation

- Gesundheits- & Fitness tracker
  - Wearable „Self-Tracking“
- DIY-/ Maker Trend
- ITO: BaKaRoS Projekt
  - Baukasten
  - Optische Systeme mit kostengünstiger Hightech.
  - Applikation: Heimdiagnostik,

http://sbmag.net/wp-content/uploads/2015/09/Fitness-Tracker-image.jpg

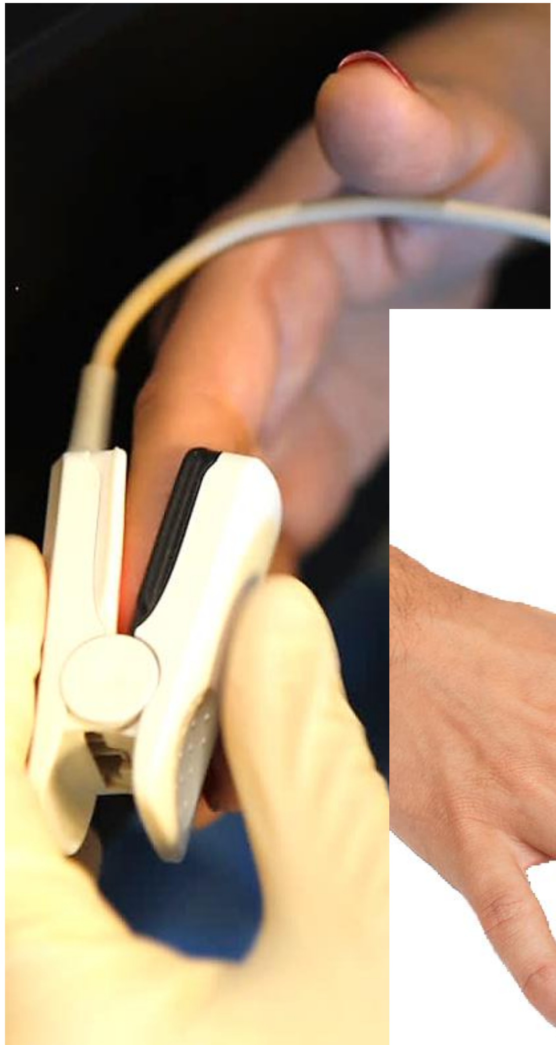


https://www.wired.com/images_blogs/about/2011/03/April-Cover3.jpg

Aufgabe

- Pulse Oximeter
  – Medizinprodukt
  – Optische Sensorkomponenten
  – Einfaches Messprinzip
  – Weltweit bekannt – klinisches Vitalzeichen
    - ähnl. EKG, etc.
    - Sauerstoff-Zufuhr bzw. -Sättigung im Blut
  – Wearable Smart-Sensor

    als Baukasten-System



http://il8.picdn.net/shutterstock/videos/

http://www.mobihealthnews.com/sites/default/files/config_00e886f8ce7ecc174ea7f15bcd01ec195aa06ef4/active/MightySat.jpg

Lösungsansatz

- Bausatz (Prototyp) + Aufbau-Anleitung + Code
  - Konstruktions-Vorgehen nach VDI 2221

Recherche

- Grundlagen: Physiologie, Prinzip
- Stand der Technik
- Normen, Gesetze

Konzepte

- Anforderungen
- Erstellung Konzepte
- Teile suchen, testen und auswählen

Design

- CAD
- PCB-Layout
- 3D Druck
- Programm

Test

- Montage/ Aufbau Prototyp
- Programmierung
- Datenerfassung/ Messung

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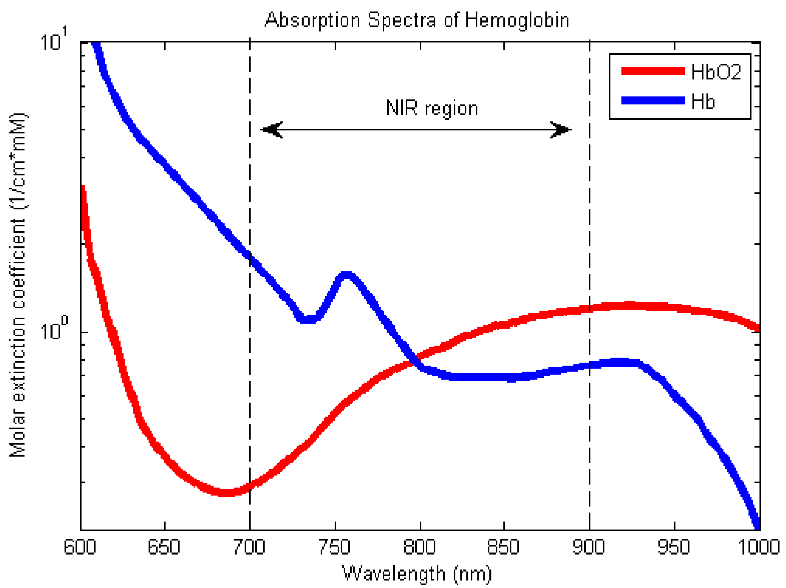
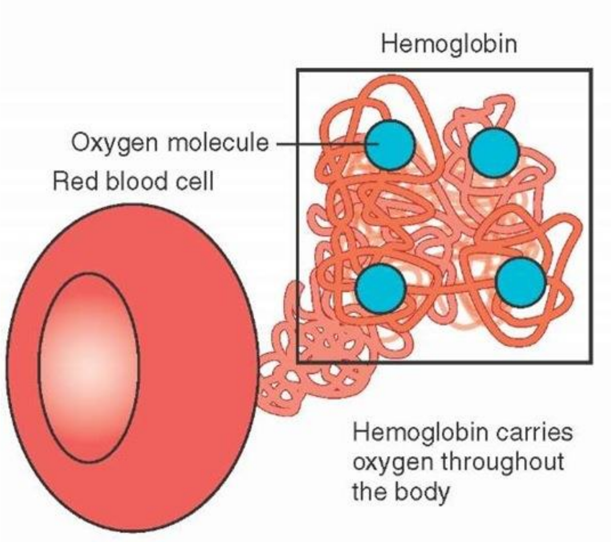
Physiologie

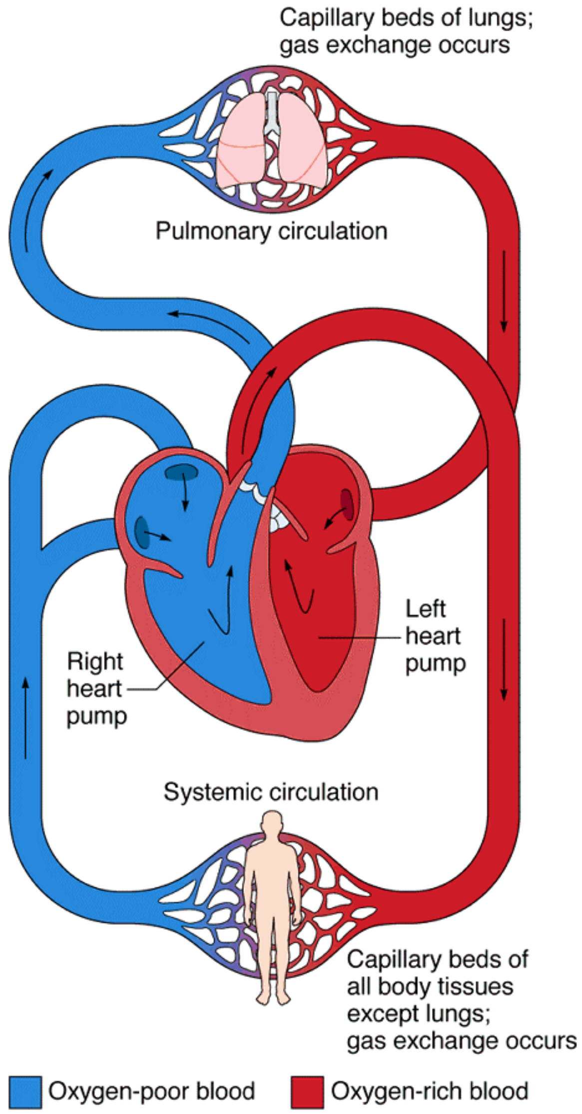
- O_2 → lebenswichtig (Hypoxämie)
- Blut – Erythrozyten – Protein: Hämoglobin (Hb)
- Unterschied Hb ↔ HbO_2
  - Sauerstoff gebunden
  - Optische Absorption je Wellenlänge



https://upload.wikimedia.org/wikipedia/commons/6/6e/Oxy_and_Deoxy_Hemoglobin_Near-Infrared_absorption_spectra.png



http://what-when-how.com/wp-content/uploads/2012/04/tmp2A83_thumb1.jpg



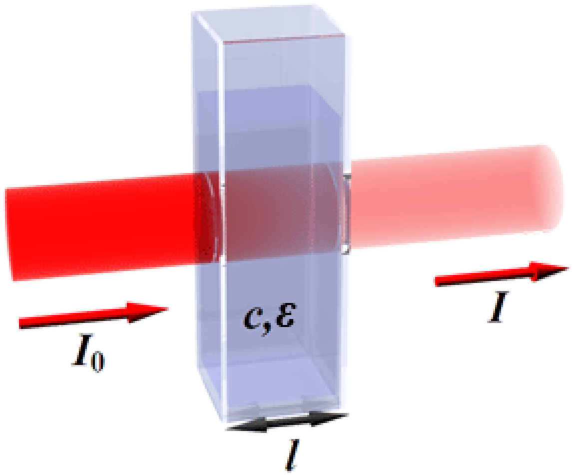
https://classconnection.s3.amazonaws.com/190/flashcards/2360190/gif/med12111c_blood_volume1357938236617.gif

Pulse Oximeter Prinzip (1)

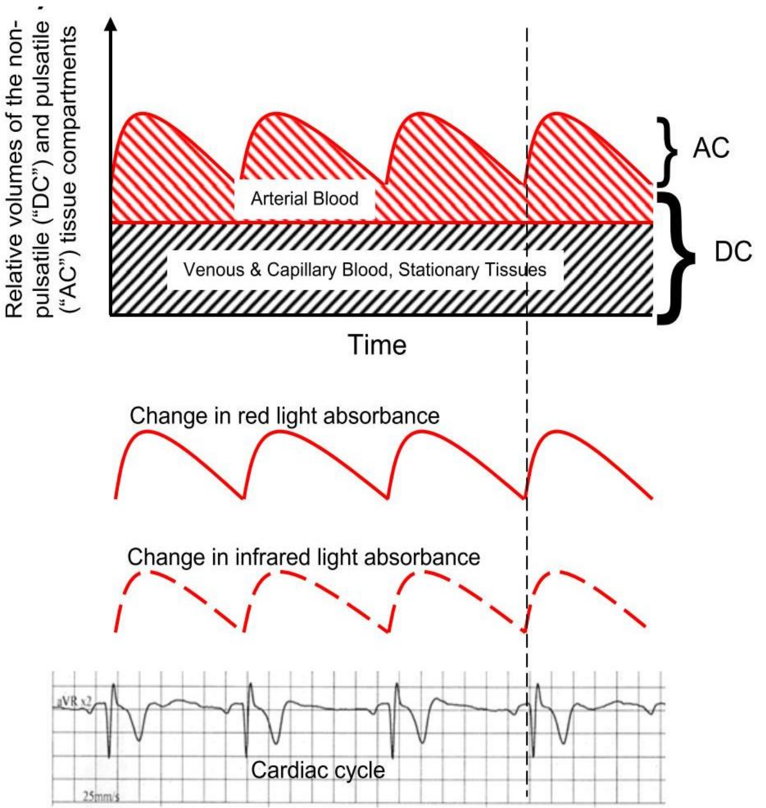
- Messprinzip:
  - Spektrophotometrie
    - Lambert-Beer-Gesetz:

$$I = I_0 \cdot \ e^{-\varepsilon(\lambda)\cdot c \cdot l}$$

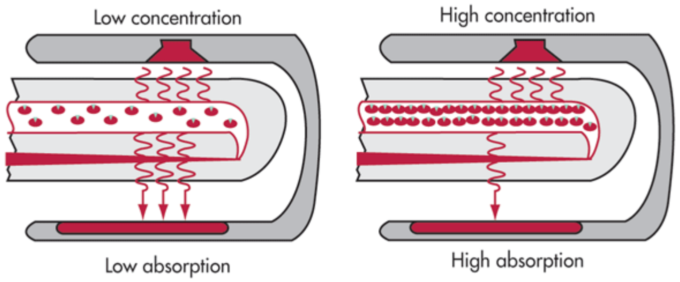
  - Photoplethysmografie PPG
    - Pulsartige Wellenform der Absorption
    - Herzschlag - Synchron
- Analyse von Hämoglobin
  - Absorptionsdifferenzen messen bei λ=660nm & 910nm
    - Sauerstoffreich vs. -arm



http://gecko-instruments.de/media/Kemtrak/beerlambert.gif



Chan, et al. 2012



http://electronicdesign.com/site-files/electronicdesign.com/files/uploads/2013/07/0905DSTI_FIG1.gif

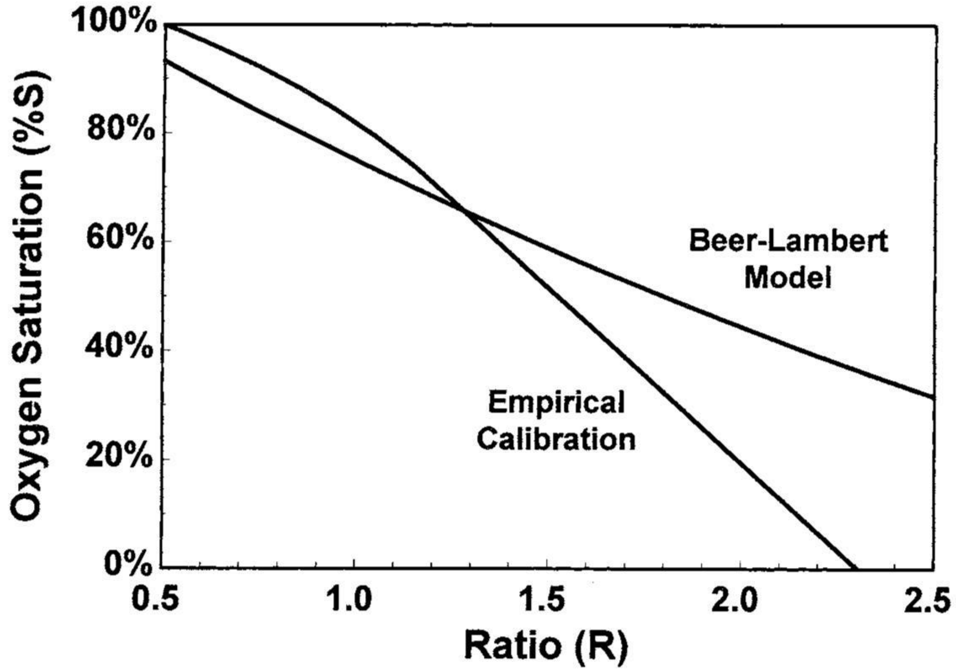
Pulse Oximeter Prinzip (3)

- Theoretische O_2 -Sättigung
  - $S_aO_2 = \frac{\varepsilon_{Hb}(\lambda_R) - \varepsilon_{Hb}(\lambda_{IR}) \cdot R}{\varepsilon_{Hb}(\lambda_R) - \varepsilon_{HbO_2}(\lambda_R) + [\varepsilon_{HbO_2}(\lambda_{IR}) - \varepsilon_{Hb}(\lambda_{IR})] \cdot R} \cdot 100\%$
  - R-Quotient:

$$R = \frac{A_R}{A_{IR}} = \frac{A_{R,AC}/A_{R,DC}}{A_{IR,AC}/A_{IR,DC}} \approx \frac{\ln(I_{\mathrm{min,R}}/I_{max,R})}{\ln(I_{\mathrm{min,IR}}/I_{max,IR})}$$

- Praktische Annäherung
  - Empirische Kalibrierungskurve

    z.B.: $\%S_pO_2 = 108 - 20R - 0.375R^2$
  - Vergleich Messdaten
    CO-Oximeter - Pulse oximeter



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Stand der Technik

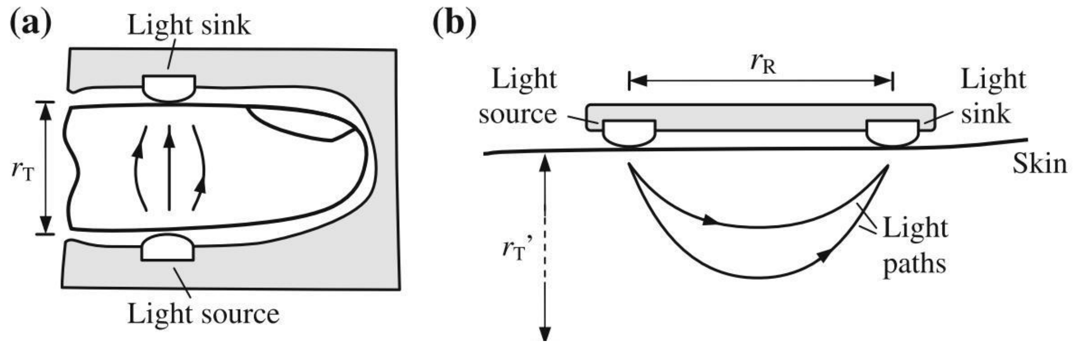
- Klinische Geräte vs. Ambulant- & Heimdiagnostik

http://www.draeger.com/sites/assets/PublishingImages/Products/ane_Primus/Modal/D-8103-2009.jpg

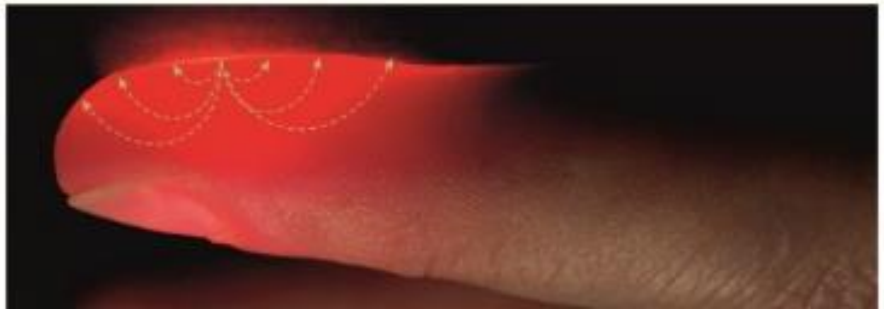
https://upload.wikimedia.org/wikipedia/commons/7/7d/Wrist-oximeter.jpg

http://www.mobihealthnews.com/sites/default/files/config_00e886f8ce7ecc174ea7f15bcd01ec195aa06ef4/active/MightySat.jpg

- Messmethode bzw. Messeinheit



[Kaniasus, 2012]

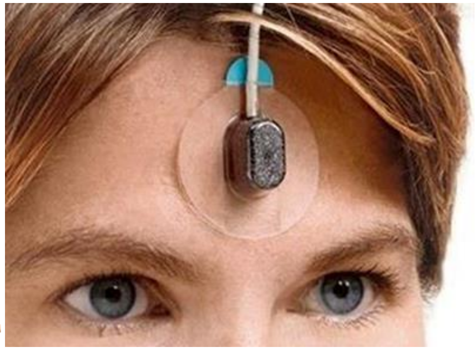


http://imagebank.osa.org/getImage.xqy?img=OG0kcC5sYXJnZSxib2UtNS04LTI1MzctZzAwMQ

- Fehlerquellen und Einschränkung
  - Optische-/ Elektromagnetische Inferenz
  - Bewegung
  - Dyshämoglobine
  - …

http://www.accutest.net/pulse-oximeter-sensors/grphx/UniHingeHand.png

http://www.medtronic.com/content/dam/covidien/library/global/en/product/pulse-oximetry/nellcor-reusable-spo2-sensors-with-oximax-features.jpg

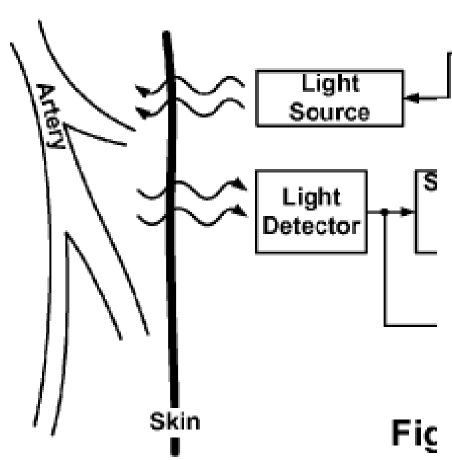


http://images.tigermedical.com/Products/LargeImages/NON8000R.jpg

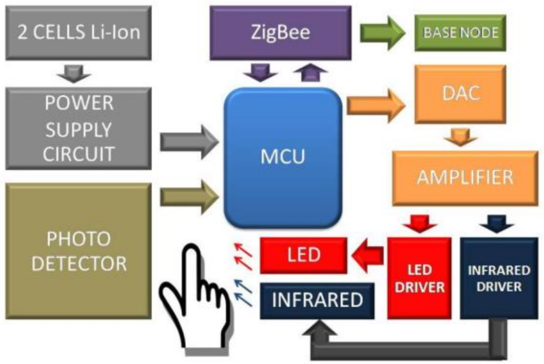
https://www.medical-world.co.uk/ProductFiles/product/nonin208000q.jpg

Konzepte

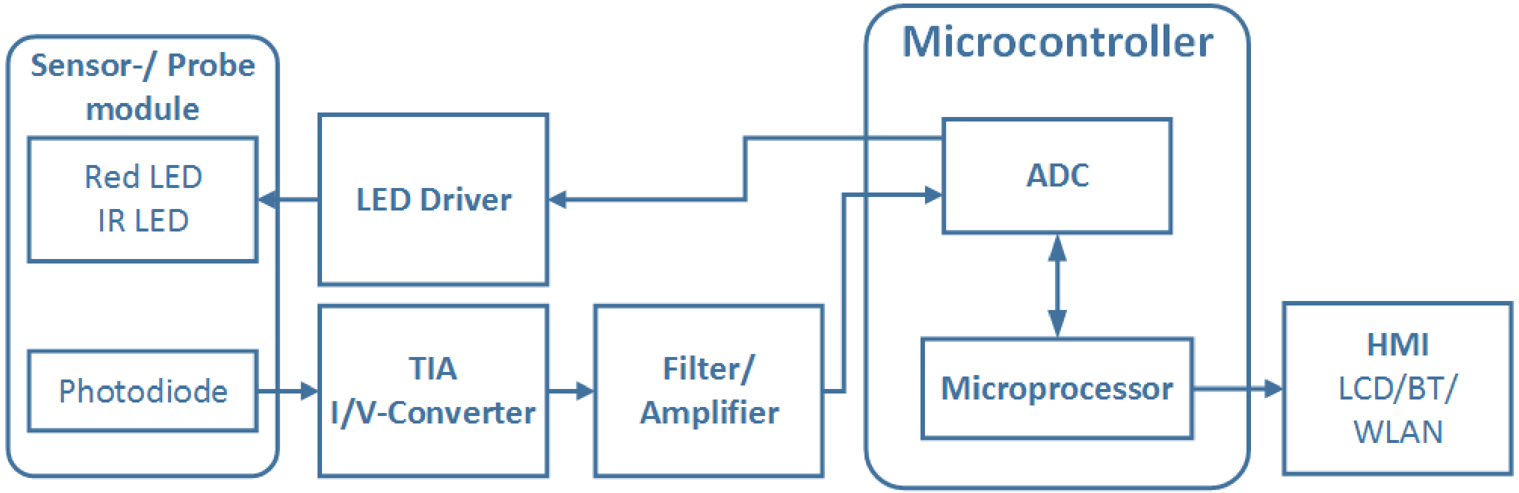
- Anforderungen an Kit
  - Kostengünstig (<50€)
  - Standard-Bauteile
  - Puls, O_2-Sättigung
  - Design:
    - Einfach, ergonomisch
    - Tragbar/ Stationär
- Ableitung von…
  - Kommerziellen Produkten
  - Prototypen
  - Ideen/ Patenten



Patent: US 8,948,832 B2 (FitBit)



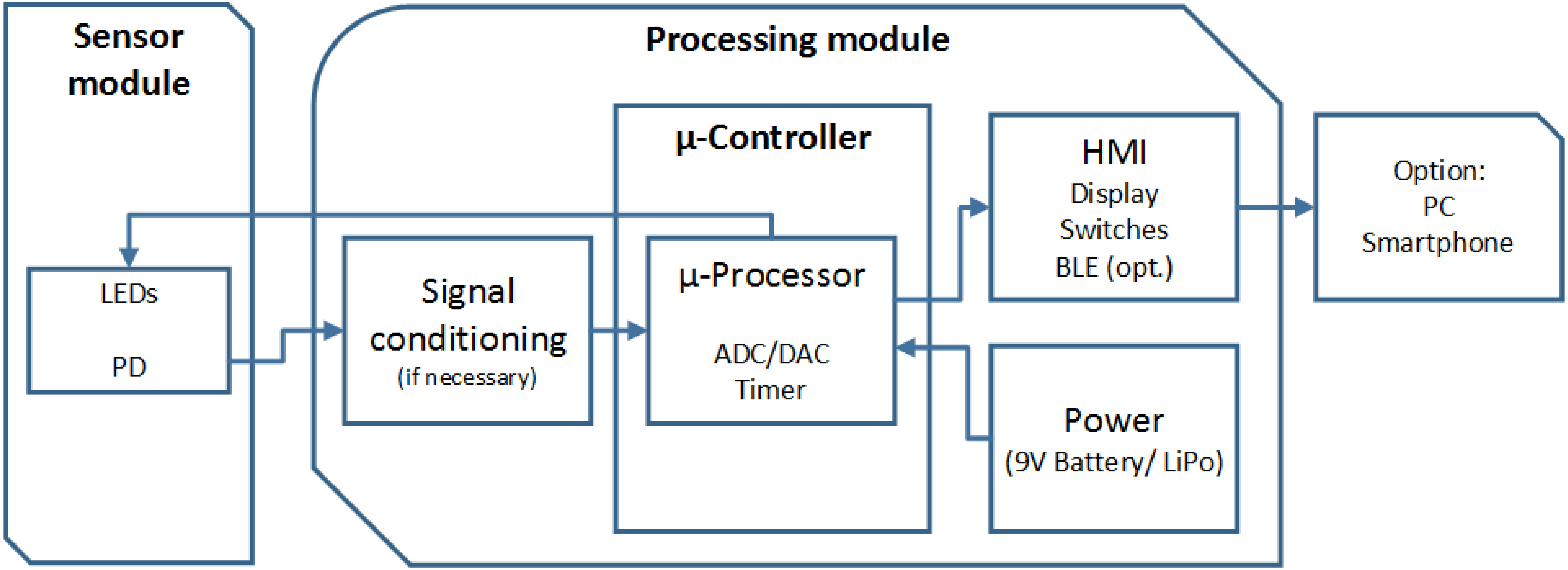
Loma, et al. 2014



Konzept Design

- Modularer Aufbau:

  Sensor | Controller | HMI



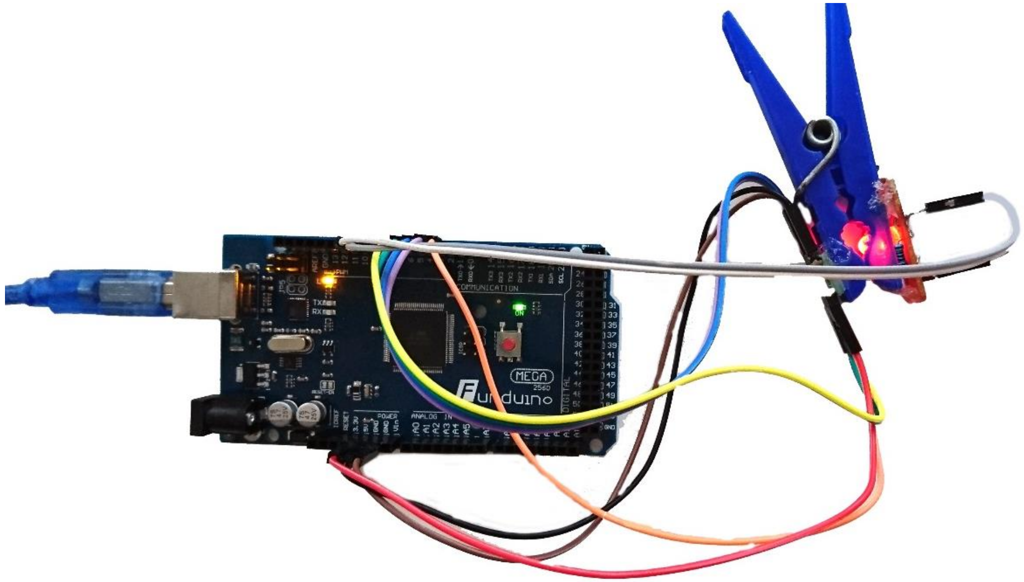
Bauteile

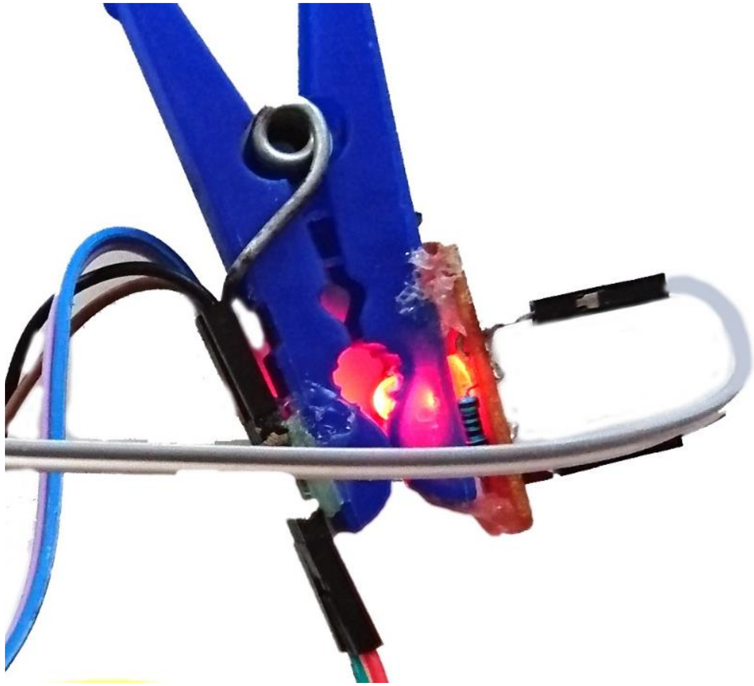
- Auswahl

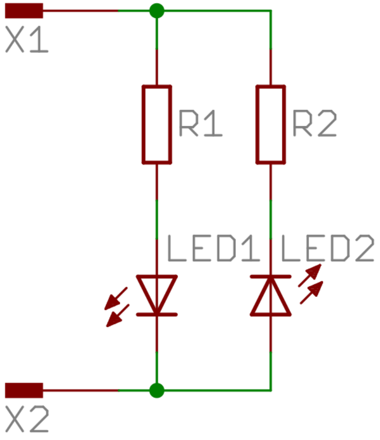
Bauteil	Eigenschaften/ Anforderungen	Auswahl
Beleuchtung (LED)	Standard LED, i_f=50mA Rot: 3-10cd IR: 5-15mW/sr	SSL-LX5093; LTE3371
Detektor (PD)	Breite Bandbreite (400-1000nm); λ_{peak}=800nm; Schnell; geringer Dunkelstrom → IC Chip (LVC/ LDC/ LFC)	PD-LFC: TSL230ARD
MCU	GPIO, einfache Programmierung und Handhabung; Kostengünstig	Arduino Uno (-Nano)
HMI	Digitales Display, Ein-Aus-Schalter, …	1“OLED Display I^2C-Treiber; Kippschalter; USB-Kabel
Funk	Kabellose Verbindung zu PC/Smartphone/etc.	BT, WLAN, ZigBee → zu teuer
Strom-versorgung	Angepasst an Arduino Spec‘s: 5-12V, ~500-1000mAh	9V-Block (LiPo)

Vor-Prototyp

- Test der Bauteile (Funktion, elektr. Steuerung)
- Positionierung:
  - Transmission - Finger
- Schaltung → LED Charlieplexing

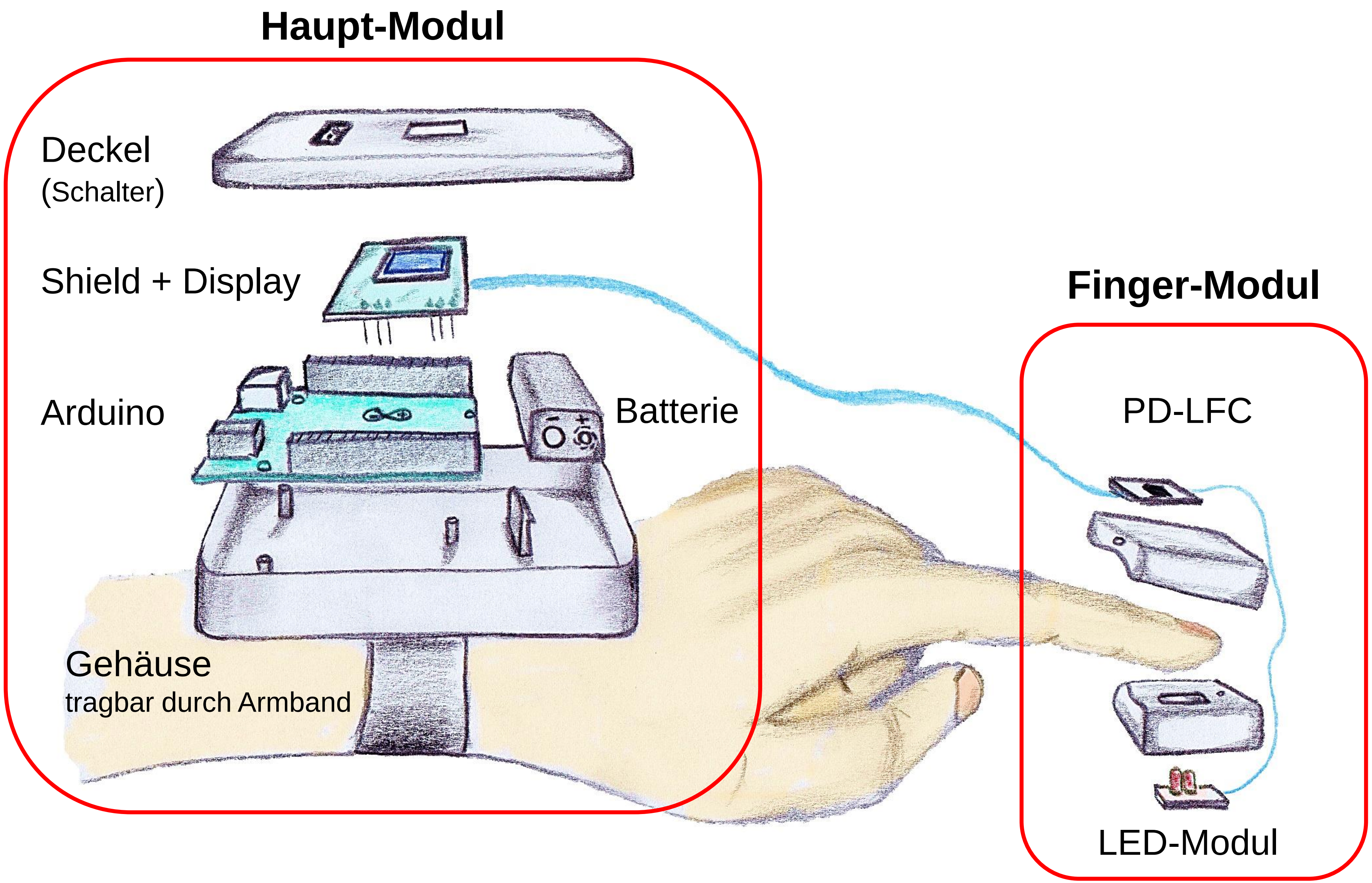






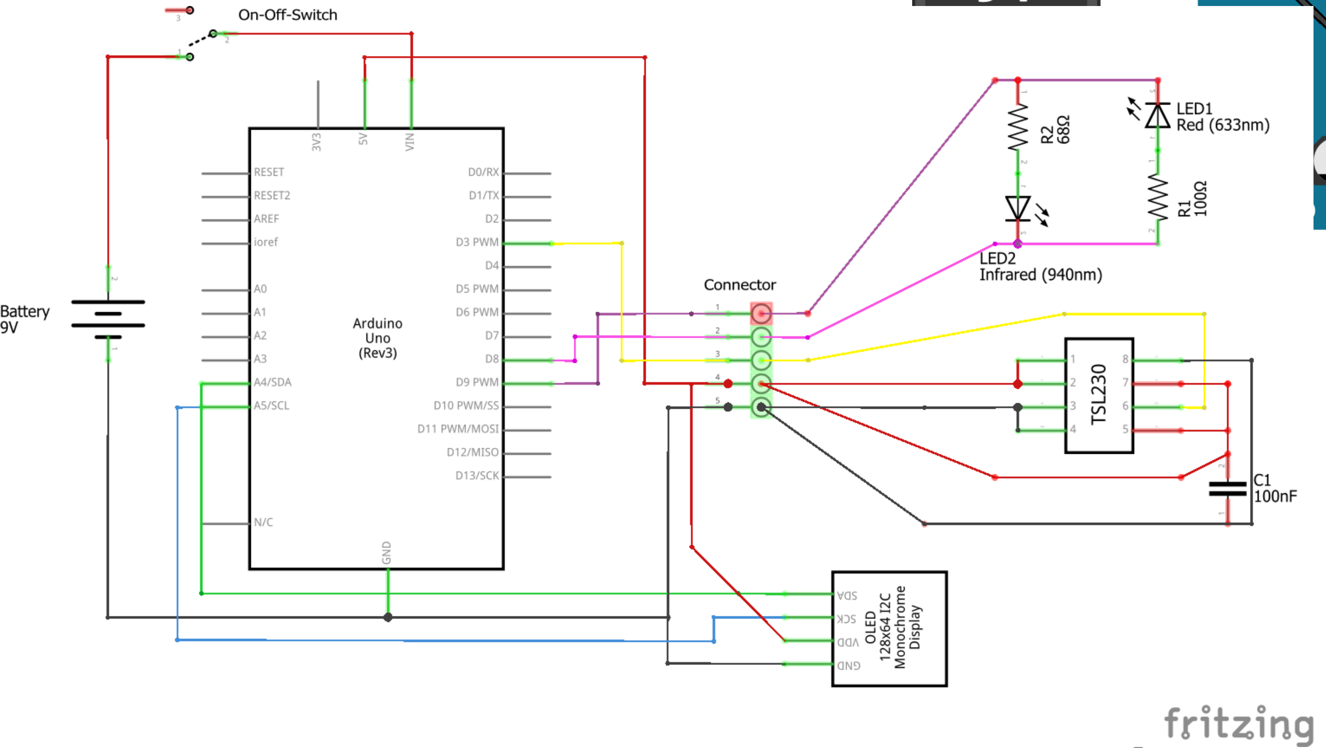
https://upload.wikimedia.org/wikipedia/commons/a/af/2-pin_Charlieplexing_with_individual_resistors.svg

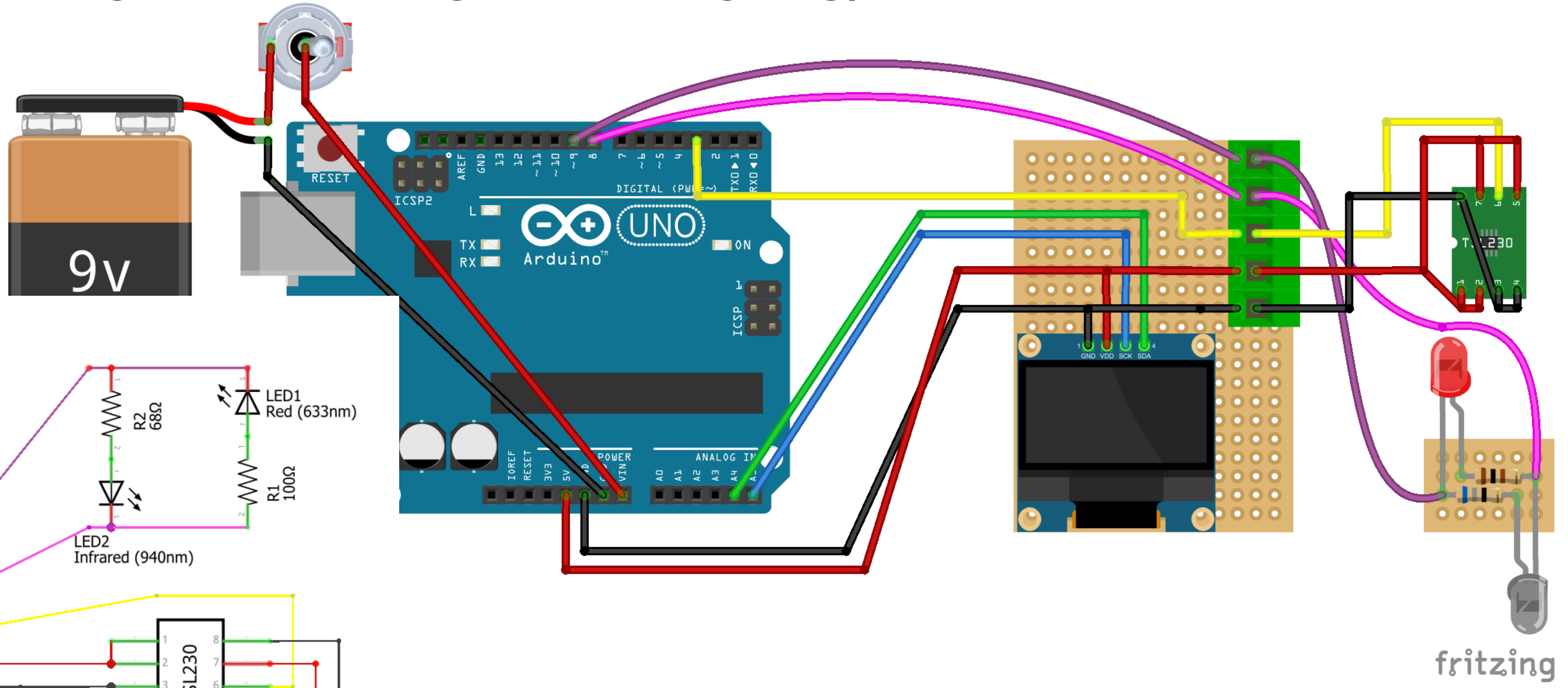
Prototyp – Design



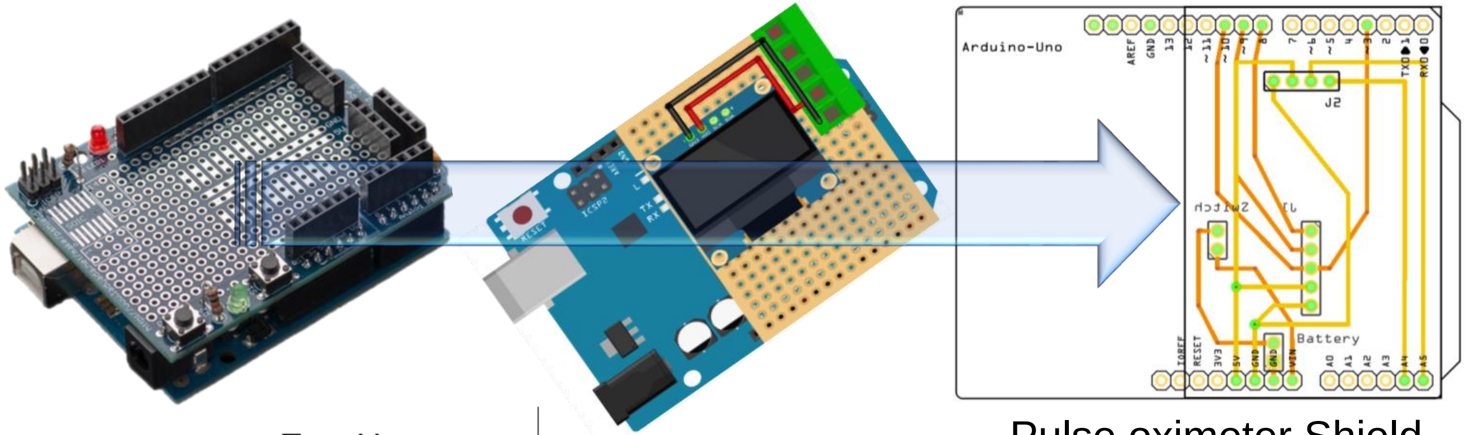
Prototyp – Elektronik

- Planung: Elektrische Schaltung/ Shield
  - fritzing Software (Schaltung, PCB Design & Fertigung)





www.arduino.cc



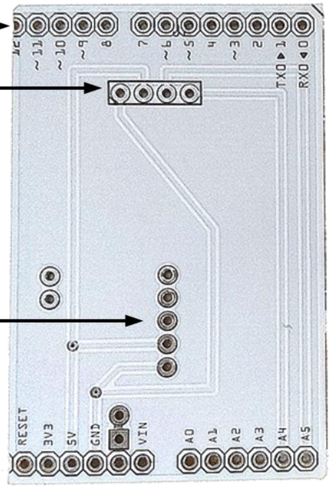
Pulse oximeter Shield

Top side

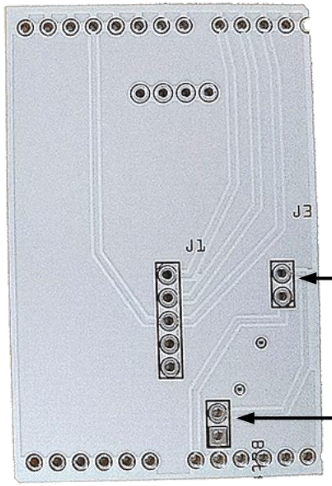
Arduino header pin
[as labeled]

Display pin holes
[GND, Vin, SCK, SCL]

Connector contacts
[D8;
D9;
D10/D3;
5V;
GND]



Bottom side

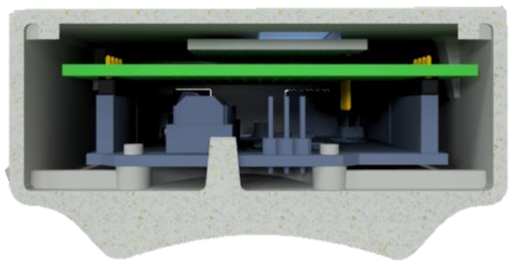


Switch
[in;
out]

Battery
[+;
-]

Prototyp – Gehäuse

- Entwicklung in 3D CAD (Inventor)
  - Ergonomische Maße (DIN33402)
  - Kunststoff-Konstruktionsregeln
  - Schraubenfrei durch Schnapphaken
- 3D Druck – Gehäuse
  - Formlabs 1+ SLA Drucker



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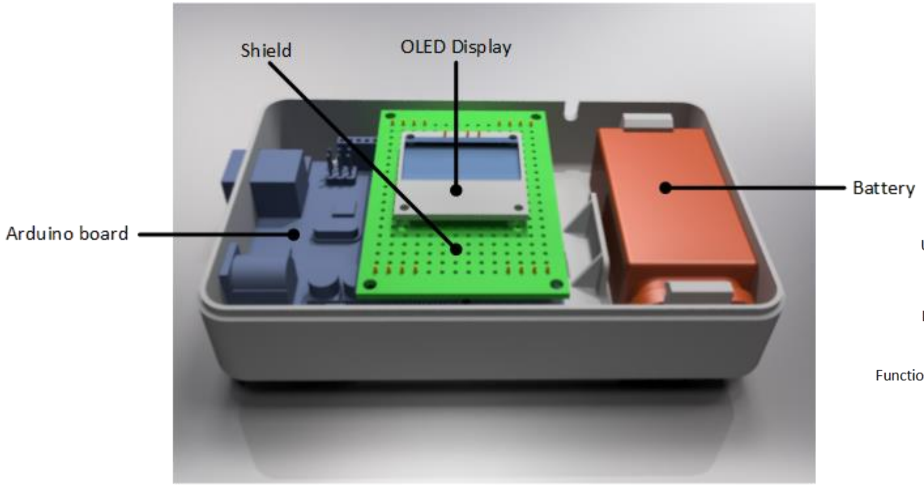
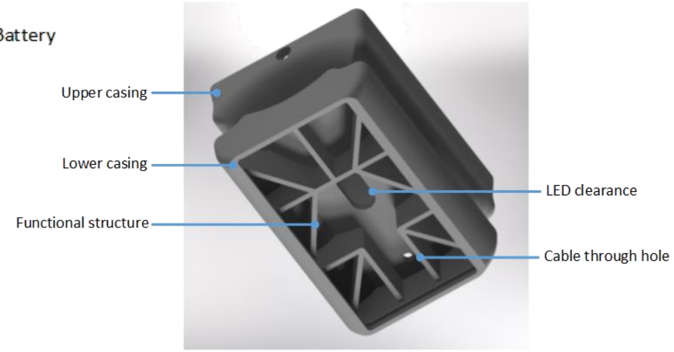
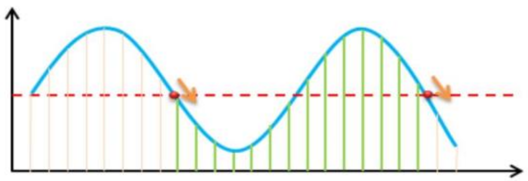
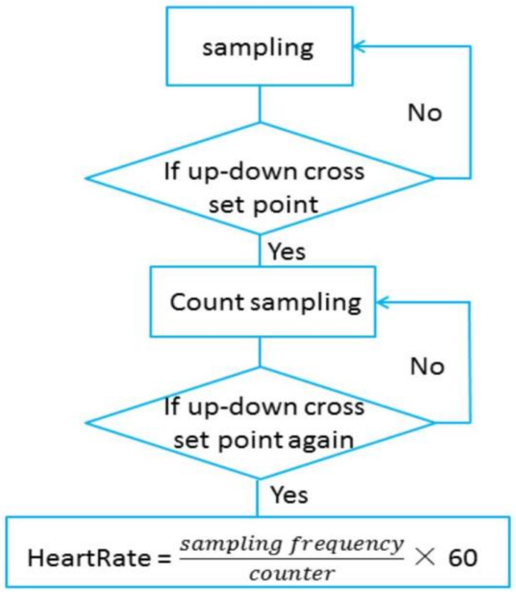




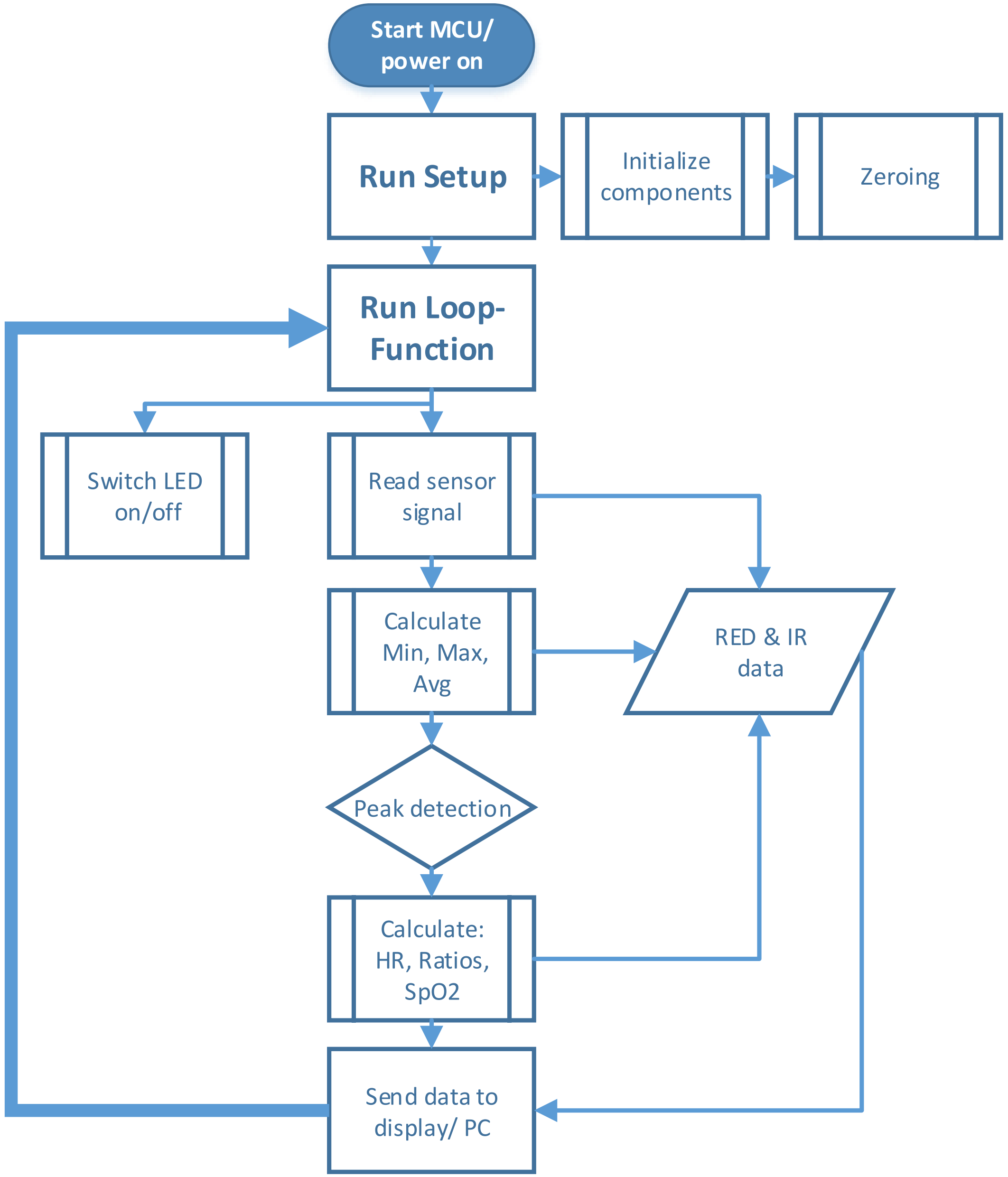
Prototyp – Code

- Programmierung
  - Arduino-C
  - Software design/ Programm-Flow





Kong, Qin, et al. 2014



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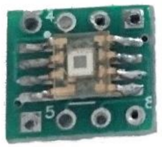
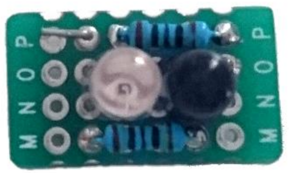
Ergebnis – Prototyp

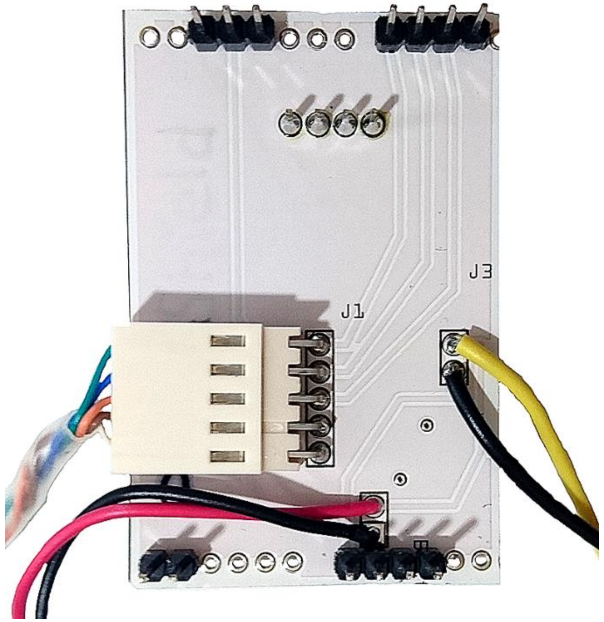
- Shield und Module
- Prototyp Kit - Zusammenbau

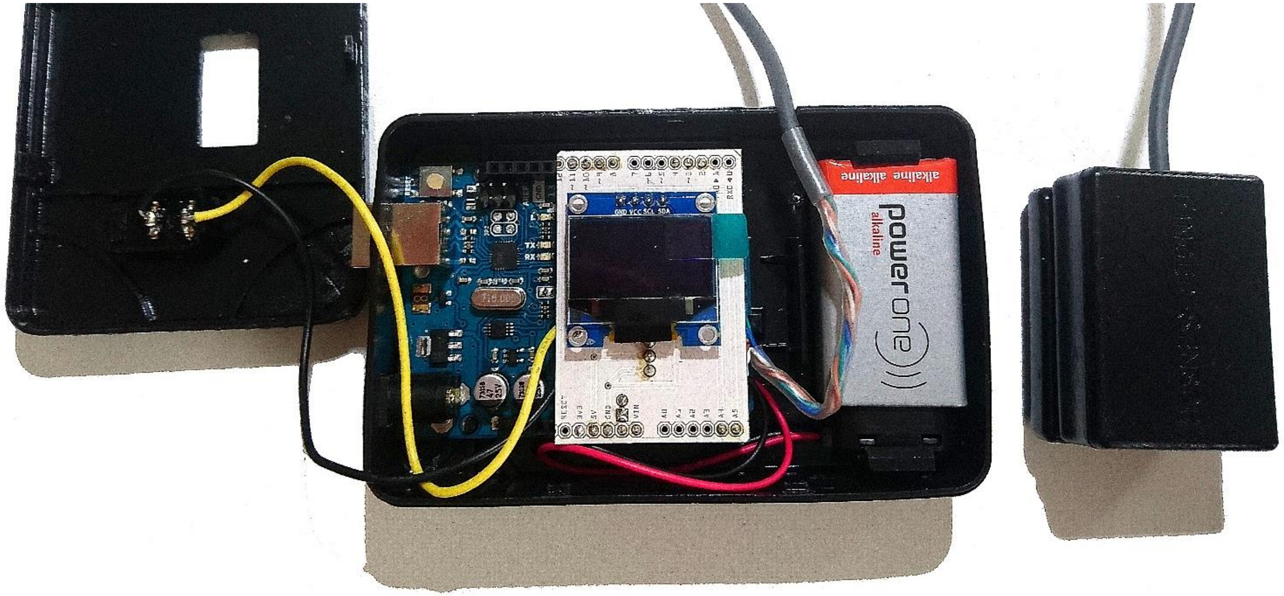
PD-Module:
TSL230 on SOIC-adapter

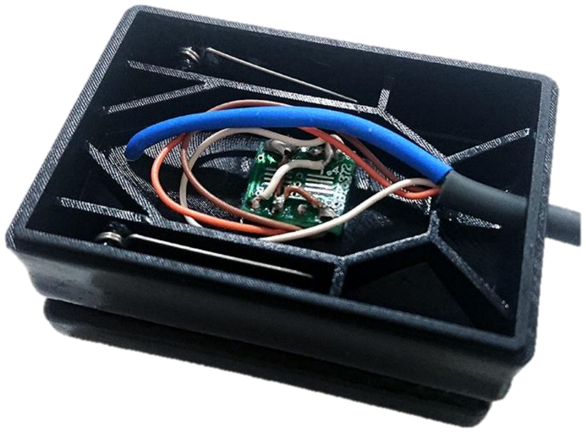


LED-Module:
custom PCB with LEDs and
protective resistors

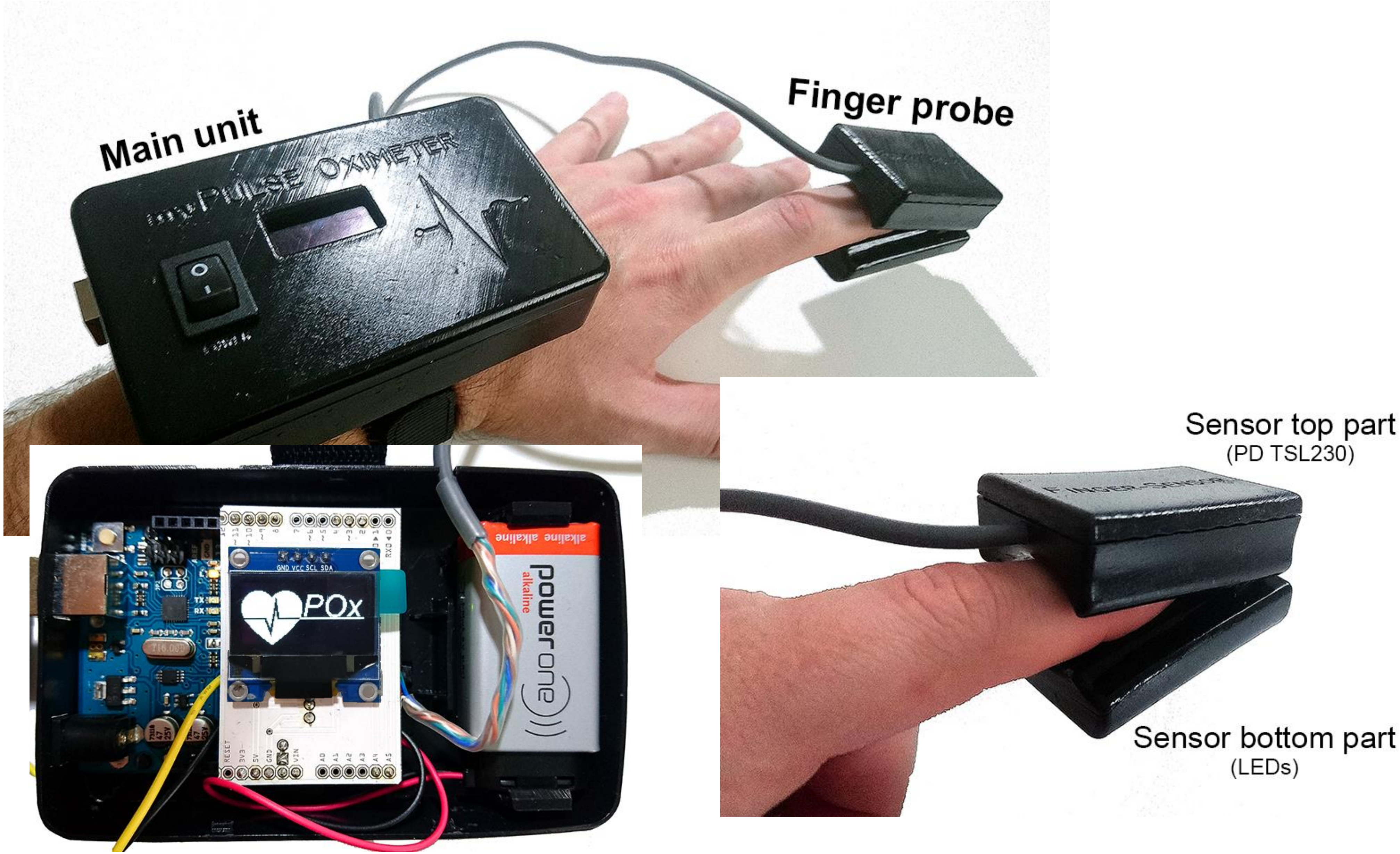






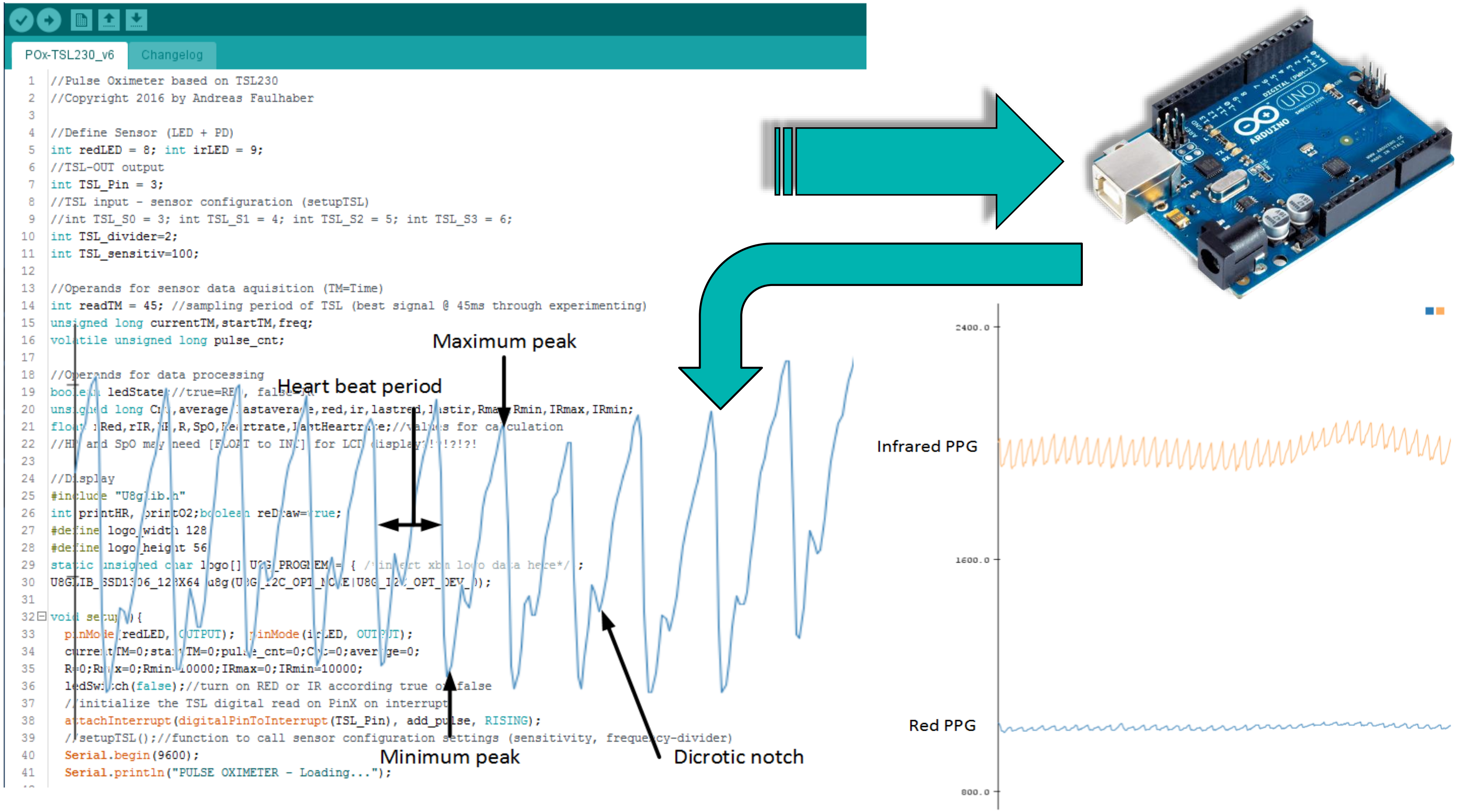


Ergebnis – Prototyp

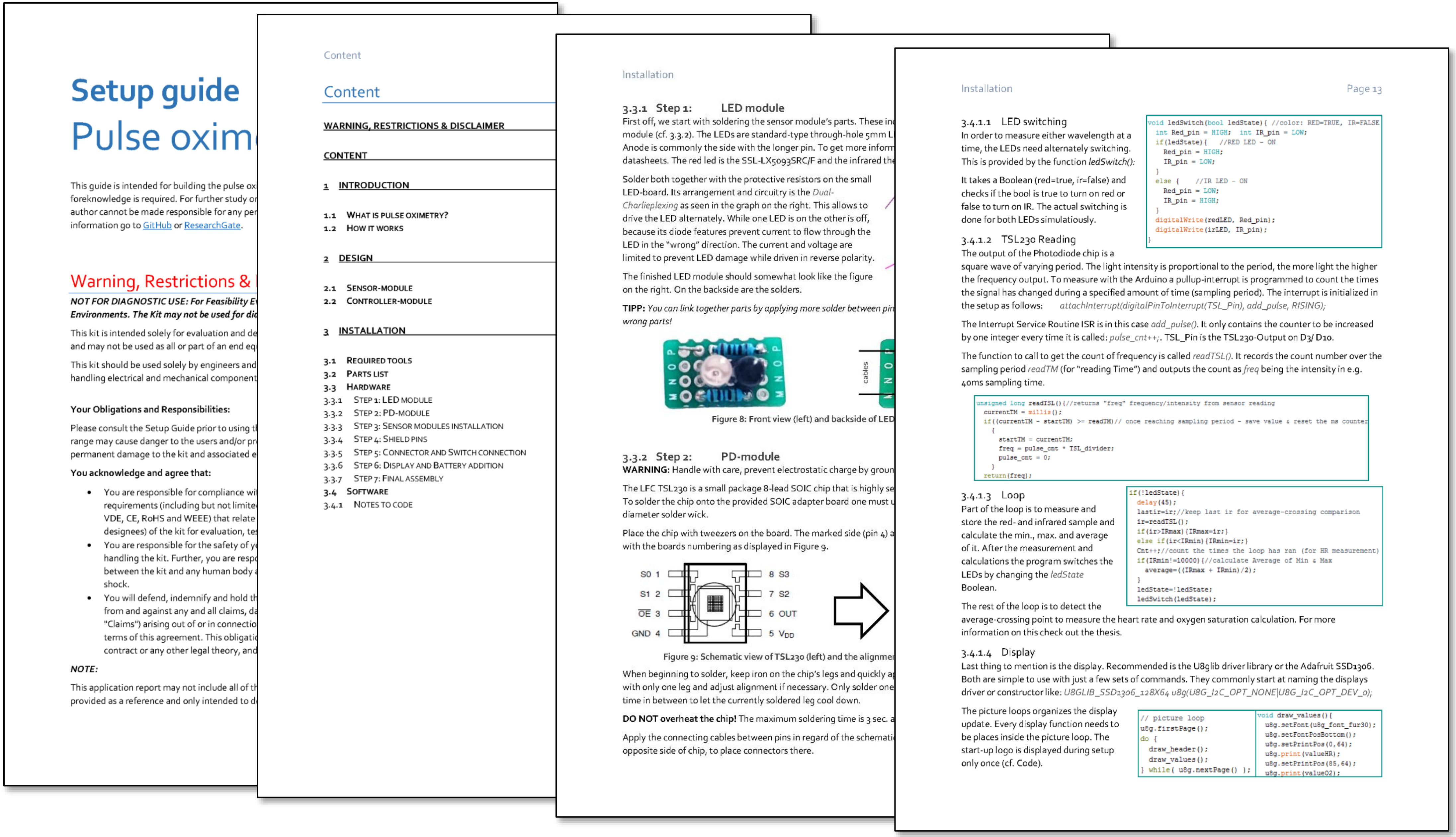


Ergebnis – Funktion

- Programmcode & Testmessung



Ergebnis – Anleitung



Setup guide

Pulse oxim

This guide is intended for building the pulse ox
foreknowledge is required. For further study or
author cannot be made responsible for any per
information go to GitHub or ResearchGate.

Warning, Restrictions &

NOT FOR DIAGNOSTIC USE: For Feasibility E
Environments. The Kit may not be used for dia

This kit is intended solely for evaluation and de
and may not be used as all or part of an end eq

This kit should be used solely by engineers and
handling electrical and mechanical component

Your Obligations and Responsibilities:

Please consult the Setup Guide prior to using t
range may cause danger to the users and/or pr
permanent damage to the kit and associated e

You acknowledge and agree that:

- You are responsible for compliance wi
requirements (including but not limite
VDE, CE, RoHS and WEEE) that relate
designees) of the kit for evaluation, tes
- You are responsible for the safety of y
handling the kit. Further, you are resp
between the kit and any human body a
shock.
- You will defend, indemnify and hold th
from and against any and all claims, da
"Claims") arising out of or in connectio
terms of this agreement. This obligatio
contract or any other legal theory, and

NOTE:

This application report may not include all of th
provided as a reference and only intended to d

Content

Content

Installation

3.3.1 Step 1: LED module

First off, we start with soldering the sensor module's parts. These inc
module (cf. 3.3.2). The LEDs are standard-type through-hole 5mm L
Anode is commonly the side with the longer pin. To get more inform
datasheets. The red led is the SSL-LX5093SRC/F and the infrared the

Solder both together with the protective resistors on the small
LED-board. Its arrangement and circuitry is the *Dual-Charlieplexing* as seen in the graph on the right. This allows to
drive the LED alternately. While one LED is on the other is off,
because its diode features prevent current to flow through the
LED in the "wrong" direction. The current and voltage are
limited to prevent LED damage while driven in reverse polarity.

The finished LED module should somewhat look like the figure
on the right. On the backside are the solders.

TIPP: *You can link together parts by applying more solder between pin*
wrong parts!

cables

Figure 8: Front view (left) and backside of LED

3.3.2 Step 2: PD-module

WARNING: Handle with care, prevent electrostatic charge by groun

The LFC TSL230 is a small package 8-lead SOIC chip that is highly se
To solder the chip onto the provided SOIC adapter board one must u
diameter solder wick.

Place the chip with tweezers on the board. The marked side (pin 4) a
with the boards numbering as displayed in Figure 9.

S0 1 | 8 S3
S1 2 | 7 S2
OE 3 | 6 OUT
GND 4 | 5 VDD

Figure 9: Schematic view of TSL230 (left) and the alignmer

When beginning to solder, keep iron on the chip's legs and quickly ap
with only one leg and adjust alignment if necessary. Only solder one
time in between to let the currently soldered leg cool down.

DO NOT overheat the chip! The maximum soldering time is 3 sec. a

Apply the connecting cables between pins in regard of the schemati
opposite side of chip, to place connectors there.

Installation Page 13

3.4.1.1 LED switching

In order to measure either wavelength at a
time, the LEDs need alternately switching.
This is provided by the function *ledSwitch()*:

```
void ledSwitch(bool ledState){ //color: RED=TRUE, IR=FALSE
  int Red_pin = HIGH;  int IR_pin = LOW;
  if(ledState){   //RED LED - ON
    Red_pin = HIGH;
    IR_pin = LOW;
  }
  else {    //IR LED - ON
    Red_pin = LOW;
    IR_pin = HIGH;
  }
  digitalWrite(redLED, Red_pin);
  digitalWrite(irLED, IR_pin);
}
```

It takes a Boolean (red=true, ir=false) and
checks if the bool is true to turn on red or
false to turn on IR. The actual switching is
done for both LEDs simultaniously.

3.4.1.2 TSL230 Reading

The output of the Photodiode chip is a square wave of varying period. The light intensity is proportional to the period, the more light the higher the frequency output. To measure with the Arduino a pullup-interrupt is programmed to count the times the signal has changed during a specified amount of time (sampling period). The interrupt is initialized in the setup as follows: *attachInterrupt(digitalPinToInterrupt(TSL_Pin), add_pulse, RISING);*

The Interrupt Service Routine ISR is in this case *add_pulse()*. It only contains the counter to be increased by one integer every time it is called: *pulse_cnt++;*. TSL_Pin is the TSL230-Output on D3/ D10.

The function to call to get the count of frequency is called *readTSL()*. It records the count number over the sampling period *readTM* (for "reading Time") and outputs the count as *freq* being the intensity in e.g. 40ms sampling time.

```
unsigned long readTSL(){//returns "freq" frequency/intensity from sensor reading
  currentTM = millis();
  if((currentTM - startTM) >= readTM)// once reaching sampling period - save value & reset the ms counter
    {
      startTM = currentTM;
      freq = pulse_cnt * TSL_divider;
      pulse_cnt = 0;
    }
  return(freq);
```

3.4.1.3 Loop

Part of the loop is to measure and
store the red- and infrared sample and
calculate the min., max. and average
of it. After the measurement and
calculations the program switches the
LEDs by changing the *ledState*
Boolean.

```
if(!ledState){
  delay(45);
  lastir=ir;//keep last ir for average-crossing comparison
  ir=readTSL();
  if(ir>IRmax){IRmax=ir;}
  else if(ir<IRmin){IRmin=ir;}
  Cnt++;//count the times the loop has ran (for HR measurement)
  if(IRmin!=10000){//calculate Average of Min & Max
    average=((IRmax + IRmin)/2);
  }
  ledState=!ledState;
  ledSwitch(ledState);
```

The rest of the loop is to detect the average-crossing point to measure the heart rate and oxygen saturation calculation. For more information on this check out the thesis.

3.4.1.4 Display

Last thing to mention is the display. Recommended is the U8glib driver library or the Adafruit SSD1306. Both are simple to use with just a few sets of commands. They commonly start at naming the displays driver or constructor like: *U8GLIB_SSD1306_128X64 u8g(U8G_I2C_OPT_NONE|U8G_I2C_OPT_DEV_0);*

The picture loops organizes the display
update. Every display function needs to
be places inside the picture loop. The
start-up logo is displayed during setup
only once (cf. Code).

```
// picture loop
u8g.firstPage();
do {
  draw_header();
  draw_values();
} while( u8g.nextPage() );
```

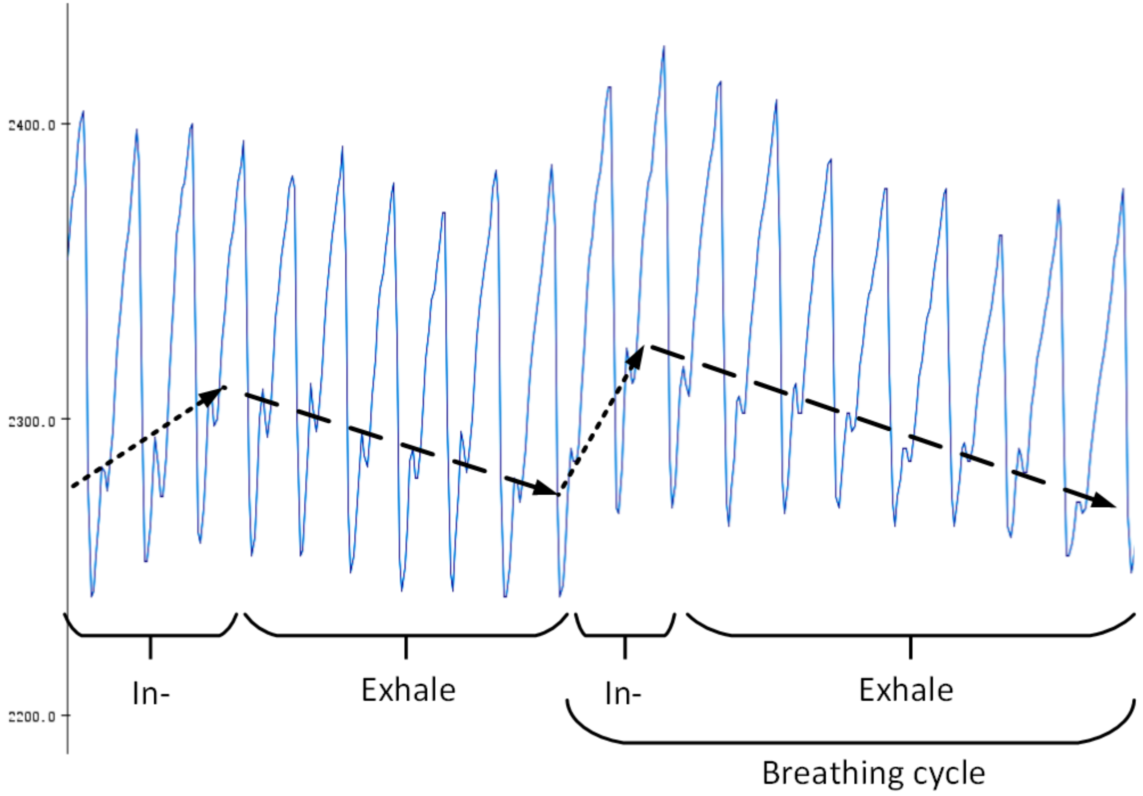
```
void draw_values(){
  u8g.setFont(u8g_font_fur30);
  u8g.setFontPosBottom();
  u8g.setPrintPos(0,64);
  u8g.print(valueHR);
  u8g.setPrintPos(85,64);
  u8g.print(valueO2);
```

Gliederung

- Einleitung
- Grundlagen
- Konzeption
- Ergebnis
- Fazit & Ausblick

Zusammenfassung

- Open-source Baukasten: Pulse Oximeter
  – Kostengünstige „Standard“-Komponenten (LED, LFC)
  – Arduino-Mikrocontroller; Programmierung leicht erlernbar
- Messung:
  – Herzrhythmus
  – Blut-Sauerstoff-Sättigung
  – PPG Wellenform
    - Dikrotische Kerbe
    - Atemrhythmus
    - Patho-physiol. Anzeichen
      (Herz-Arhythmie, Schlafstörung, uvm.)



Ausblick

- Geräte-spezifische Kalibrierung

  → Notwendig für S_pO_2-Bestimmung
- Verbesserungen am Programm

  → Maxima-Detektion; Signalverarbeitung; FFT
- Potential zur Kosteneinsparung

  Unter Ziellimit (€46,20 < 50€)

  → Direktbezug – chinesische Hersteller
- Erweiterbar bzw. Nutzbar für weitere Projekte
  - Lichtquellen/ -intensität vermessen
  - Turbidimetrie

Vielen Dank!

Thank you!

谢谢!

Tusen Takk!