Simplified open HW/SW pulse oximetry interface for purpose of COVID-19 symptoms detection and monitoring

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Abstract— **A low cost, simplified hardware and software interface capable of measuring and analyzing photoplethysmogram signal is presented in this paper. Two most important vital signs, oxygen saturation and heart rate are extracted, while the same principle can be extended to other parameters associated to this signal. Overall system consists of specially designed analog front-end, based on the off-the-shell components and microprocessor of modest processor and memory capabilities, like Arduino series. In addition to hardware simplification, the optimized software algorithms for signal acquisition, process handling, on-chip signal processing, feature extraction and basic communication are demonstrated. Satisfactory and repeatable results are obtained with accessibility to raw signal. Developed interface is a low-cost alternative to expensive OEM solutions, especially suitable for its integration in wearables, telemedicine and IoT healthcare systems in process of COVID-19 diagnosis and treatment. The design challenges, starting idea, system architecture, implementation details and preliminary testing results are shortly elaborated.**

Keywords- Covid-19, Arduino, symptoms, oxygen saturation, low-cost, interface, SpO2, heart rate, PPG

I. Introduction

Early detection of COVID-19 symptoms is of vital importance for fighting this illness, which has changed our lives. If we detect the symptoms earlier, the chances of recovery are better. Patients with COVID-19 have had a wide range of symptoms, appearing 2-14 days after exposure to the virus. Common symptoms include fever, breathing problems, cough, and tiredness. They can expand to muscle aches, chills, sore throat, runny nose, headache, chest pain, pink eye (conjunctivitis), nausea, vomiting, diarrhea, ash etc. The severity of symptoms ranges from very mild to severe and older people have a higher risk of serious illness. The basic instruments (self-measuring wearables), which we must possess in every home to detect COVID-19 symptoms are body thermometer, oxygen saturation meter, known as pulse oximeters, and respiration rate meter. Many people with COVID-19 have low level of oxygen in their blood (hypohemia), even when they feel well. Low oxygen saturation (SpO2<94% in absence, or SpO2<88% in the presence of chronic lung disease, can be an early warning sign that medical care is needed and leading to pneumonia, followed by other respiratory complications [1]. A 1 °C rise in body temperature can increase heart rate by 8.5 beats per minute (b.p.m.) on average. Measuring the heart rate in different conditions (resting, during sleep) can be a useful diagnostic tool. The pulse oximetry features, most frequently Oxygen Saturation (SpO2) and Heart Rate (HR), are extracted from Photoplethysmography (PPG) signal. In addition to SpO2 and HR, numerous parameters can be extracted from PPG signal, as it is shown in Table 1. Obviously, the PPG becomes very important signal in non-invasive, inexpensive, and convenient diagnostic tool.

On the market, there are plenty pulse oximeters in the form of low-cost wearables, which are practical to use, low power, behind significant visualization features [2]. Their accuracy might be questionable, and they present very closed systems, without possibilities to be easy integrated in wider Cyber Physical (CPS) or Internet of Things (IoT) systems, where the accessing a raw signal and proper communication interfacing are prerequisites. OEM solutions for pulse oximetry (PO) are in fact system on boards, quite expensive, operated by specific ASIC circuits or microprocessors with closed software/firmware. They are compatible with specific probes and each of them has specific communication protocols. Fig. 1a) shows an example of Nonin's OEM III OEM.

In order to overcome the problems of OEMs, several vendors developed systems on chip for PO. Typical examples are SOCs from Maxim's 30xx series is shown in Fig. 1c). Even being fully integrated, their use for clinical purposes is questionable, behind poor software support and complex adjustments. The specific 3D printing enclosure probe needs to be designed, if we want to get out usable signal, without noise and artifacts. To solve limitations of usage ready wearables, expensive OEMs and complex and unreliable PPG SOCs, many researchers design their own probes and connect them to open microcontroller platforms, Fig. 1 b). This is time and labor consuming solution, never giving good results. However, some of the solutions intend to solve design problem of complex PPG analog front-end by connecting sensors directly to microprocessors [3] or implementing the simplest analog or digital interfacing. As example, measuring heart rate only (pulse meters) and parameters which are associated to this basic signal [4].

TABLE I. SOME OF THE PARAMETERS THAT CAN BE EXTRACTED FROM RAW PPG SIGNAL USEFUL FOR COVID-19 SYMPTOMS DETECTION

#	Par.	Description
1	SpO2	Oxygen saturation. One of the main parameters of the respiratory and blood transportation system
2	HR	Heart (Pulse) Rate
3	HRR	Heart Rate Rhythm
4	RHR	Resting Heart Rate
5	HRV	Heart Rate Variability
6	PI	Perfusion index and Pleth Variability Index (PVI)
6	ARD	Arrhythmias detection
7	SAD	Sleep apnea detection
8	PPGP	Photoplethysmogram parameters, Systolic Amplitude, Pulse Width, Pulse Area, Peak to Peak Interval, Pulse Interval, Augmentation Index, Large Artery Stiffness Index
9	FDPP GP	First Derivative Photoplethysmogram Parameters, Systolic peak position, Diastolic peak position, dT, Crest time (CT),
10	SDPP GP	a, c, d, e points and adequate ratios, as example, ratio b/a, Ratio c/a, Ratio d/a, APG (Acceleration PlethysmoGram) parameters
12	PD	Prediction of diabetes
13	SD	Stress detection

Generally seen, front-ends for detection and acquisition PPG signal have common architecture. LED drivers provide alternating red (RED) and infrared (IR) lighting of finger or ear lobe. The receiving signal is detected with wide photo detector and further amplified by transimpedance amplifier and voltage amplifiers, which simultaneously filtering DC and AC components.

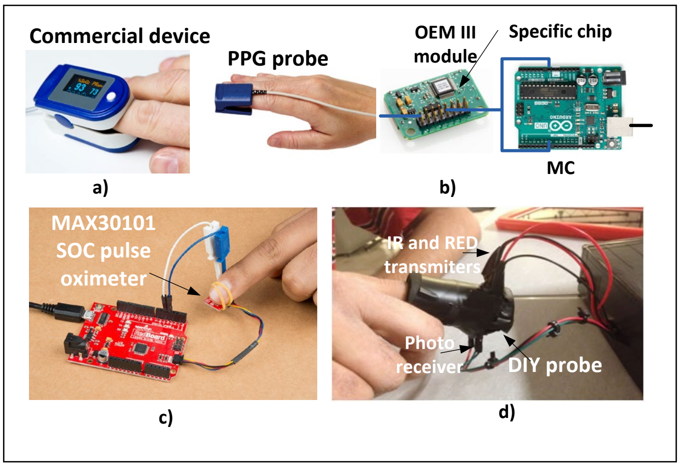

Figure 1. Interfaces for pulse oximetry: a) commercial pulse oximeter, b) OEM based, b) system on chip (SOC) [7], and c) hand made [8]

Sometimes, the circuits for automatic gain control, ambient light cancelation etc. are added to the design. Overall process is managed by microcontroller. In fact, interfacing is not simple, and its complexity is proportional to the required accuracy, which very often should be below 3%. Thus, the challenge of designing feasible and enough quality PO interface remains and it is more pronounced, with appearance of open microprocessors and IoT platforms [5]. Simple, we need to monitor SpO2 and HR anytime, anywhere, especially in case of COVID-19 pandemic [6].

In this paper we propose an interface for PO, that is low-cost and of satisfactory accuracy. It consists of front-end, realized in different configurations, Arduino based microcontroller and basic software routines for control, signal processing and features extraction were applied.

II. PROPOSED PPG INTERFACE

Having in mind mentioned considerations, a feasible PPG interface has been proposed, shown in Fig. 2. where the standard (market) PPG probe is used for sensing. Analog-front end is based on the off-the-shelf components, while the function of the CPU is entrusted to cheap microcontrollers, as those from ATiny and ATmega series. Using factory PPG probe instead of produced in house has several advantages. It is difficult to self-build sensor enclosure that will provide a good fitting on the finger or ear lobe, while at same time being protected from external noise, such as light fluctuations and artifacts.

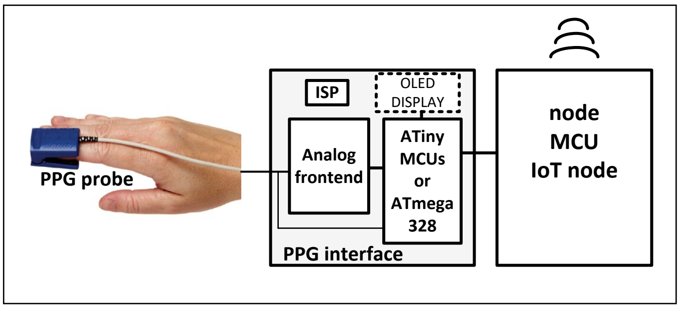

Figure 2. Combination of factory probe and PPG interface based on-the-of-the-shelf analog components and microcontrollers

The professionally produced PPG probes are cheaper than self-made having in mind labor cost and time spend for production. At the end, professionally produced ones are of better accuracy, sometimes certified for clinical purposes. Front-end and low-cost microcontroller, makes an interface easy to connect to the IoT nodes, as example MCU ESP32 can drive such probe on the IoT interface side.

III. FEASIBLE PPG FRONT-END

A. Driver Circuit

PPG probe/sensor consists of IR and RED transmitting LED diodes and photo-diode receiver shown in Fig. 3 a). The constant equal currents through IR and RED branches are, provided by special drivers, based on MOSFET's or transistor bridges. In our design, we simplify such drivers, using, only, two external resistors, driven by 3 GPIO pins, Fig. 3 b). The values for R1 and R2 are chosen to provide equal currents through IR and RED LEDs, IRED=IIR, ie., Vcc/RA=Vcc(R1+R2). R2 is selected to compensate lower voltage drop of IR diode. Three pins A, B and C alternate in firing LEDs, by changing to different modes, INPUT (HiZ) or OUTPUT, as shown in Fig. 3 b).

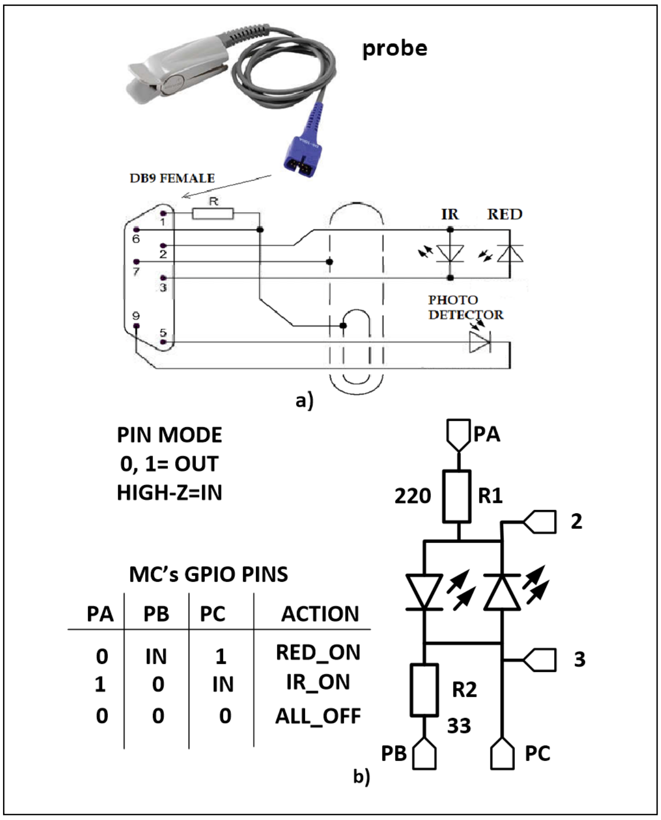

Figure 3. a) commercial PPG probe and DB9 pinout, b) driving a probe with 3 GPIO pins and 2 resistors.

B. Photo Receiver/Amplifier

In the simplest version, the photo amplifier can be built, only, of one transistor, Fig. 4 a). The R3 is chosen for transistor to remain in active mode. Improved version of one component amplifier is given in Fig. 4 b). It is a rail-to-rail Transimpedance Amplifier (TA). The R3 and C1 are selected to eliminate high frequency switching noise, 3.3M and 33pF. Vr provides reverse voltage for receiver diode and simultaneously shift the DC level of output signal.

The software routines for "firing" IR and RED diodes are given in Fig. 5, as well as their sequential calls from main loop. By simple driver circuit, amplifiers and adequate software routines we can sequentially fire and sample RED and IR channels and get raw PPG samples. Firing time can be adjusted, and thus consumption of driver circuit. It is interesting to note that both IR and RED channels can be acquired by one receiving amplifiers (TA), while AC component is amplified by second stage, which consists of one or two parallel AC Amplifiers (ACA), depending on timing control, Figure 5, down)

The advantages of discussed front-ends are numerous, these are simple to realize, low cost, i.e. less than 0.5$ price etc. TLC272, standard rail- to-rail OA is used. The circuits are rated as very low power, since we can deal with duty cycle of driver switching. Four pins are used for overall driving and acquisition process. Of course, circuits have several disadvantages. They present only the first amplification stage without any filtering.

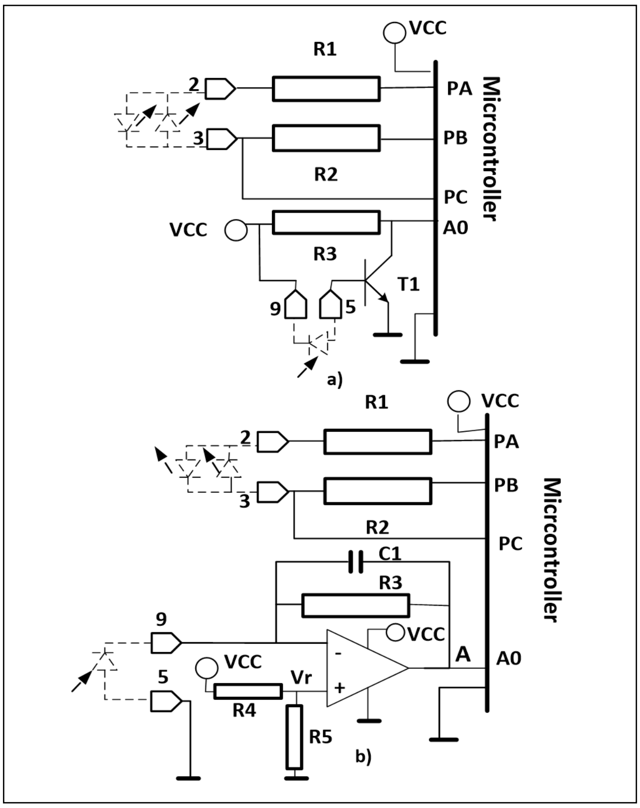

Figure 4. a) PPG amplifier in versions of one transistor, b) one amplifier.

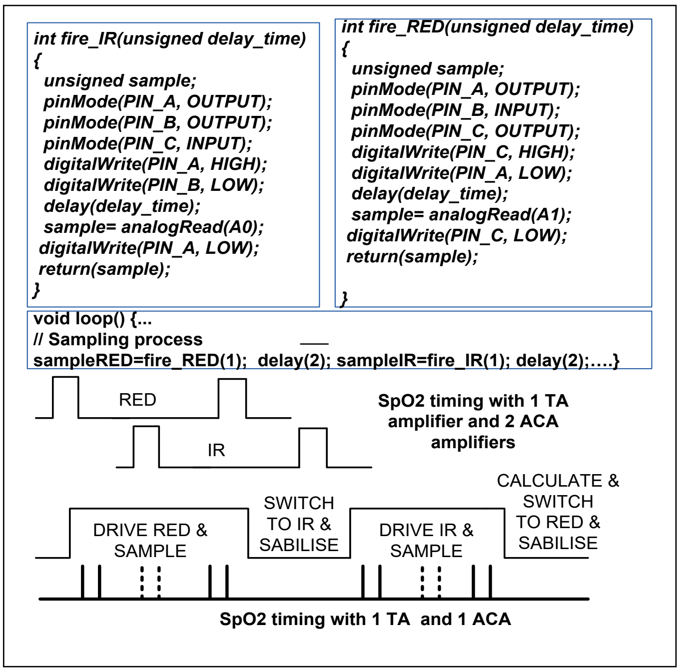

Figure 5. Software driving and acquisition of simple analog front-end, SpO2 timing when we use 1 TA and 2 ACA or 1 TA and 2 ACA

Signal, at input A0, consists of DC and AC components. It is known that AC component of both RED and IR channels is about 5-10% of DC one. That means low resolution of AC component will be achieved, because majority of the signal belongs to DC component. If we have precise A/D converter, as example 16bits, the issue of low amplitude AC fluctuations can be suppressed.

C. Improved version of PPG front-end

In order to achieve better amplification of the AC components, the above TA amplifier is extended by adding several circuits within ACA (AC Amplification) block: S&H (Sample and Hold), LPF (Low Pass Filter) and 2nd amplification stage, OA3, Fig. 6. The idea is to still use off-the-shelf components and same LED driver, behind achieving higher AC amplitude. S&H is performed by pin SW_IR_RED. This amplifier has the same DC value as after first stage and AC component amplified for ratio R3/R2. Namely, the output signal in point C has DC and AC components given as `VC=VDC(PPG)+VAMB-VAC(PPG)*R3/R2`, where VAMB is an ambient produced signal, usually of DC nature. Fig. 7 a) shows scenario of connecting ACA circuit in one or two branches, depending how we sample the blocks of RED and IR signals, simultaneously or alternately, see Fig. 7 b). In case of driving LEDs and sample and hold the "fires" routines from Fig. 5 should be adopted by adding commands of S&H, bellow listing in Fig. 8.

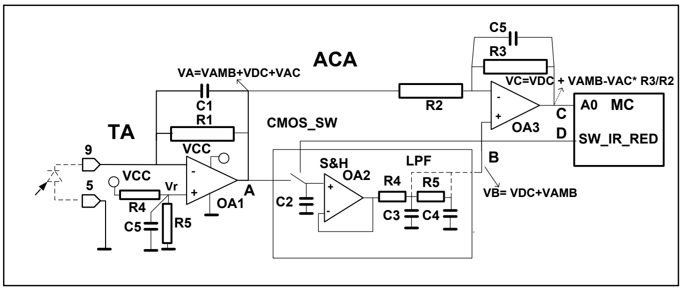

Figure 6. Improved analog front-end for PPG amplifier

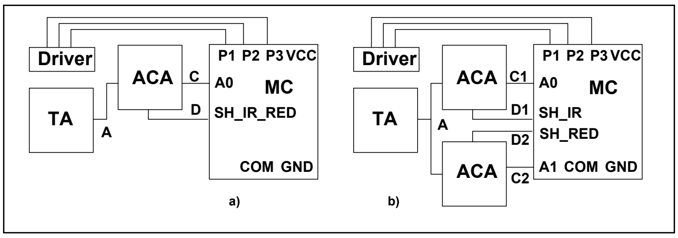

Figure 7. PPG front-ends with one (a) and two (b) ACA amplifiers

```
int fire_RED(unsigned delay_time)
{unsigned sample;
 pinMode(PIN_A, OUTPUT); pinMode(PIN_B, INPUT);
 pinMode(PIN_C, OUTPUT);
 digitalWrite(PIN_C,HIGH);digitalWrite(PIN_A, LOW);
 digitalWrite(SW_RED, HIGH); //S&H on
 delay(delay_time);sample= analogRead(A1);
 digitalWrite(SW_RED, LOW); //S&H off
 digitalWrite(PIN_C, LOW); return(sample);}
```

Figure 8. Firing with added S&H commands

IV. TESTING RESULTS

The system is tested in all configurations. Here we show the results obtained for configuration Fig. 7 (b), under the following parameters: PPG probe Nonin Adult 8000AA, microcontroller, MC Arduino UNO. The components in Fig. 6: OA(1..3)=TLC274, CMOS_SWITCHR=CD4066, 4=8.2K, R5=1.2K, R1=3.3M, C1=33pF, R2=4.7K, R3=100K, R4=750K, R5=750K, C5=0.1uF, C3=C4=2.2uF, C2=0.22uF (5%), C5=10uF, VCC=5V. Software parameters: sampling frequency, fs=32Hz, digital filter LPF of first order with cut-off frequency of 1.5Hz, HPF of first order with cut-off 0.1Hz, the number of points for FFT (FFTN=256 ponts). The fix integer FFT is selected, operating on level of one byte, char type. The input signal to fix FFT module should be reduced to signed char size, -127 to 127. The firmaware occupies: 12392 bytes (38%) of program storage space (of 32256 bytes). Global variables use 1634 bytes (80%) of dynamic memory (maximum 2048 bytes), leaving 404 bytes for the local variables. As seen, memory allocation is highly optimized, having in mind complexity of calculation, even FFT. The consumption of the circuit is mainly determined by LEDs driver and can be adjusted by duty cycle of switching LEDs. During our experiments, it was between 2mA-5mA, that is very satisfactory.

Fig. 9 illustrates RED and IR PPG signals for configuration from Fig. 7 (b) as well as normalized FFT power spectrums, from which the HR and the SpO2 are calculated.

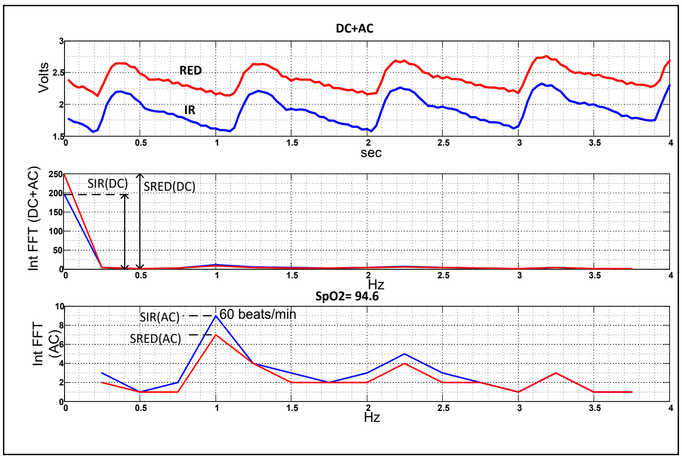

Figure 9. Obtained diagrams from proposed interface and approach of SpO2 calculation from FFT. RR= (SRED(AC))/SRED(DC))/ (SIR(AC)/SIR(DC));

The HR refer to position of dominant peak in FFT power spectrum for the case DC component of the spectrum FFT(0) is excluded. The oxygen saturation SpO2 is calculated from FFT power spectrum using following expressions:

```
((RR=MAX_AC_RED)/MAX_DC_RED) / (MAX_AC_IR/MAX_DC_IR);
SpO2=110-25*RR;
```

One should note that, using the same platform, SpO2 can be found using time domain features. As example: RR = (RMC of ACRED / MEAN of DCRED) / (RMS of ACIR / MEAN of DCIR) in signal duration of 3-4 secs, RMS is root mean square value of samples in time interval, and MEAN mean value. Also, RR could be calculated as

`RR = ((REDmax-REDmin)/REDmin)/((IRmax-IRmin)/IRmin),` where max and min are maximum and minimum values of raw RED and IR samples in time domain, usually 3-4 secs. The pseudocode in Fig. 10 is extracted from Arduino IDE and shows the calculation of SpO2 from FFT spectrum, using fixed arithmetic.

The HR resolution in Hertz is determined as `Delta(HR)=fs/FFT_N` and for fs=16Hz, could be between 3-4 beats/min. The resolution of SpO2 calculation in comparison to Nonin OEM III module was less than 3%.

```
//Finding SpO2 from FFT Spectrum for FFT_N points
….
#include "fix_fft.h"  //Include fix_t libraray
….
//define variables for fix fft
char im[FFT_N], data_dc_red[FFT_N], data_dc_ir[FFT_N],
data_ac_red[FFT_N], data_ac_ir[FFT_N];
if(k> FFT_N) //when the number of samples exceed
FFT_N(256){
  .......
//SPO2 calculation
      for(i=0; i<FFT_N; i++) im[i]=0;
      //RED FFT DC
      fix_fft(data_dc_red, im, 8, 0);  //Call Fix FFT
      MAX_DC_RED = sqrt(data_dc_red[0] * data_dc_red[0]
      + im[0] * im[0]); //Spectrum(0)
      //IR FFT DC
      for(i=0; i<FFT_N; i++) im[i]=0;
      fix_fft(data_dc_ir, im, 8, 0); //Call Fix FFT
      MAX_DC_IR = sqrt(data_dc_ir[0] * data_dc_ir[0] +
      im[0] * im[0]);
      //HR from IR and finding maximum in FFT AC RED
      // Spectrum
      dat=0;
      HR_RED=0;
      MAX_AC_RED=0;
      for(i=0; i<FFT_N; i++) im[i]=0;
      fix_fft(data_ac_red, im, 8, 0);
      for (i = 1; i < FFT_N/2; i++)
            {
            dat = sqrt(data_ac_red[i] * data_ac_red[i] +
            im[i] * im[i]);
            if (dat> MAX_AC_RED) {HR_RED=i;
             MAX_AC_RED=dat;}
            }
       //Finding maximum in FFT AC IR Spectrum
      dat=0;
      HR_IR=0;
      MAX_AC_IR=0;
      for(i=0; i<FFT_N; i++) im[i]=0;
      fix_fft(data_ac_ir, im, 8, 0);
      for (i= 1; i < FFT_N/2; i++)
            {
            dat = sqrt(data_ac_ir[i] * data_ac_ir[i] +
            im[i] * im[i]);
             if (dat> MAX_AC_IR) {HR_IR=i;
               MAX_AC_IR=dat;}
            }
      //Calculate RR
      float A= float(MAX_AC_RED)/float(MAX_DC_RED);
      float B= float(MAX_AC_IR)/float(MAX_DC_IR);
      RR=A/B;
      ........
      //Calculate SpO2
      SpO2=110-25*RR;
      ...... }
```

Figure 10. Pseudocode extracted from Arduino IDE, shows the calculation of SpO2

V. CONCLUSIONS

In this paper we have presented the design of PPG front-end interface, suitable for research and professional purposes, based on the off-the shelf components and open microprocessor platforms, such as Arduino. Two most important vital signs, oxygen saturation and heart rate are extracted, from obtained raw PPG signal. The specific version of the LEDs driver is proposed as well as configuration of amplifiers front-ends, starting from simplest to improved ones. All versions of proposed circuits are useful for amateurs or professional application. The main software routines to control LED drivers, perform acquisition and further processing in order to extract oxygen saturation and heart rate are elaborated. Satisfactory and repeatable results are obtained that makes such interface a low-cost alternative to expensive OEM solutions, especially for integration in wearables, telemedicine and IoT healthcare systems in process of COVID-19 diagnosis and treatment.

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