Optimization Design and Simulation of Signal Processing System for Motion Artifact Minimization in PPG Based Cardiac Rate Measurements

Sadiq, U.A.[123]; Ogunleye, A. M.[2]; Ebam, M.[2]; Oluyombo, O. W.[1,3]
National Space Research & Development Agency, Abuja, Nigeria[1]; Center for Satellite Technology Development, Abuja, Nigeria[2]; Electrical & Electronic Engineering Dept., University of Abuja, Nigeria[3];

Abstract- Photo-plethysmography (PPG) measurements is derived from a complex interaction between light propagation and tissue characteristics. The quality of PPG signal is determined by the sensing, cardiovascular, and biological factors. Due to the measurement principle, the PPG signals are quite sensitive to motion artefacts. Voluntary or involuntary movements produce modifications of the inner tissues (such as motion of the muscles and tendons, and compression or dilatation of the tissues) that change the content of the tissues spanned by the light and thus modify the received signals. These factors result in changes along the optical path and modify the received optical signals. In this research, the newly developed Firefly Optimization Algorithm (FOA) is proposed to solve Integrated Band Pass Filter (BPF) and pulse amplifier optimization problem. The designed signal processing system consists of a Pulse detector, signal extraction and pulse amplification circuits. The designedcardiac rate monitor shows a wide range of measurements in the range of 42 bpm at 0.7 Hz frequency to 207 bpm at 3.46 Hz frequency with a gain of 65.969 dB at 1.745 Hz mid-frequency. In addition, the FOA designed system demonstrated high sensitivity of4.97V output voltage with 2.5mV input signal and is capable of being connected to Analog-to-Digital Converter (ADC) for digital interfacing with microcontroller.

Key words- Band pass filter, Pulse detection, Signal extraction, pulse amplification, FOA, PPG.

Significance- This paper finds the optimum parameters of the integrated band pass filter and pulse amplification circuit elements. The parameters of the band pass filter and pulse amplification elements are significant for matching the output voltage of the system with ADC for microcontroller interfacing.

I. INTRODUCTION

A non-invasive cardiac rate sensing system which detects the variation of the blood flow in finger due to mechanical contraction of the heart has been proposed. Cardiac signal sensor using PPG method has traditionally been done in two modes: transmittance and reflectance of infrared light. In transmittance mode PPG, light is passing through the tissue using an infrared diode and is detected on the opposite end using a photo-detector. In contrast, reflectance mode PPG uses a photo-detector on the same side as infrared diode to detect the light reflected by the tissue. In this paper, the Infrared diode is used as a transmitter while aphoto detector is used as a receiver as shown in Figure 1.

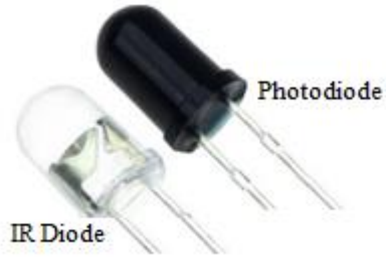

Fig.1: IR diode and photo-detector

Figure 2 represents the cardiac signal source setup with a matched pair of infrared emitting diode (SHF409) and photo detector (SFH309) used to convert the cardiac signal into electrical signal. Infrared diode (IR emitter)was used to direct infrared signal to a highly vascular surface like a fingertip. The infrared emitter and photo detector are positioned side-by-side as shown in Figure 1. The principle is based on the fact that when a fingertip is place in between the transmitter and receiver, IR light is transmitted through the fingertip while the blood circulation inside the finger causes a periodic change in the intensity of IR signal transmitted, which in turn causes a period current response in the detector.

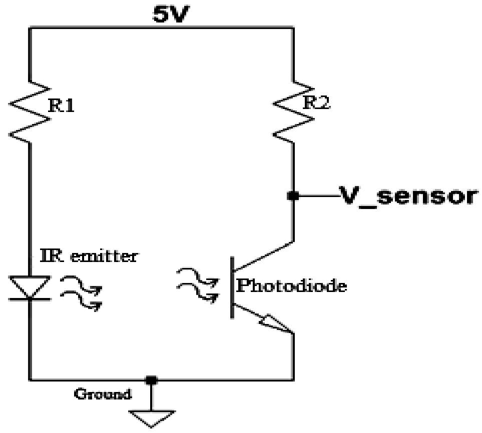

Fig.2: Cardiac Signal Detection Circuit Setup for PPG

With this, theintensity of IR signalobtained at the output of the photo-detector (Figure 2) isa function of the volume of blood in the fingertip. However, not all the IR signal incident on the fingertip will reflect back to the photo detector aspart of the infrared signal will be absorbed (Hu *et al*, 2008). As explained earlier,the intensity of the reflected infrared signal varies with the volume of blood in the fingertip, which in turn varies in accordance with frequency of the heartbeat. Specifically, lower intensity of reflected infrared signal indicates higher volume of blood and vice versa (Reisner*et al*, 2008). The PPG signal consists of two components: Alternating current signal (AC) and Direct Current (DC) signal (Lin *et al*, 2009). The AC component is superimposed of the DC component. The AC component is the result of pulsatile changes in arterial blood volume (Allen, 2007). Since this arterial blood volume is synchronous with the cardiac beat, the AC component can be used to measure the cardiac rate while the DC component is associated with the tissues, bones, and average blood volume (Raj and Jothi, 2014). This DC components of the PPG signal must be removed for effective analysis of the AC component. A plot of the variation in the intensity of infrared signal with time is known as photo-plethysmography signal (Zheng and Hu, 2007) as shown in Figure 3 (Mathieu *et al*, 2014).

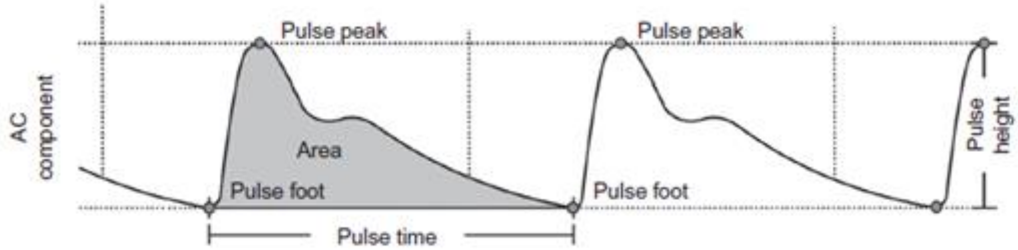

Fig.3: Typical Photo-plethysmography (PPG) Waveforms and its respective Components

As shown in Figure 3, the time period of each pulse in the signal is an indication of cardiac beat while the amplitude of the signal indicates the concentration of various constituent parts of arterial blood (Bagha and Shaw, 2011). The AC component of the infrared signal is very small and weak, which is about 2.5mV with lots of noises in the signals. However, the signal voltage required by the Analog-to-Digital Converter (ADC) is between 2.5V – 5V. Therefore, in order to enable heartbeat sensor output compatible with the ADC or microcontroller, there is need for amplification circuit to provide a steady-state output voltage in the range of 2.5V – 5V. This clearly indicates a gain of between 1000 – 2000. This implies that the pass band frequencies are amplified by a factor of 66 dB with a small signal amplifier. In order to achieve the required amplification, thegain is divided into two; amplifier gain and the filter gain. In this research, Firefly optimization algorithm (FOA), a metaheuristic algorithm, has been used to design the required bandpass filter and the pulse amplifier circuits.

The main purpose of heuristic or metaheuristic algorithms for solving combinatorial optimizationproblems is to find an optimal value under specified constraints. Some of the conventionaloptimization approaches are the analytical methods, numerical methods, heuristicmethods. Numerical optimization methods rely on computation of gradients indetermine the solution with maximum fitness (Lemonge*et al*, 2010). However, the problem with numerical optimization technique is the locality of optima (Lemonge*et al*, 2010). Stochastic optimization techniques rely on random perturbations to the solution spaceand are more adept at preventing a solution from being trapped in a local optimum for non-convex problems (Yang, 2008). However, the obvious problem with stochastic optimization techniquesis that on an average, it requires a lot more computations of alternate solutionscompared to gradient-based techniques (Yang, 2008). Many practical problems of importance are notconvex and difficult to solve in reasonable amount of time (Yang, 2008).Consequently, heuristics aredeployed to make the solution feasible in a reasonable amount of time. Heuristics is away of approximation of solution by trading optimality for speed. Meta-heuristic algorithmsare generic algorithmic frameworks that are often rooted in natural processes,such as simulated annealing, genetic algorithm and behaviour of insects. Meta-heuristicalgorithms cannot guarantee a global optimum, however they are able to provide goodsolutions in reasonable timeframe and are typically able to avoid local optima (Mladenovic&Hansen,1997).

II. FIREFLY OPTIMIZATION ALGORITHM

Firefly Optimization Algorithm (FOA) is a new nature inspired optimization algorithm developed by Yang in 2008 based on swarm intelligence and inspired by the social behaviours of fireflies for solving optimization problem (Yang, 2008). This algorithm is based on bioluminescence principle. The rhythmic flash, the rate of flashing, and the amount of time between flashes form part of the signal system that brings both sexes together (Lewis &Cratsley, 2008). The mathematical formulation of the algorithm is based on the fact that; all fireflies are unisex and therefore can communicate with anyone else (Kazemzadeh-Parsi, 2014), the attractiveness between fireflies is therefore determined by the level of brightness of the individual firefly, and the brighter firefly light attracts other fireflies (Carlos &Coello, 2000). The objective function of the problem depends on the brightness of a firefly (Ray &Liew, 2003). FOA aims to find an optimal solution to optimization design problem.

It is a known fact that the light intensity at a particular distance from the light source obeys the inverse-square law. The light intensity l decreases as the distance r increases in terms of $l \propto 1/r^2$. Furthermore, the air absorbs light, which becomes weaker and weaker as the distance increases. These two combined factors make most fireflies visible to a limited distance, usually several hundred meters at night, which is good enough for fireflies to communicate with one another. The flashing light can be formulated in such a way that it is associated with the objective function to be optimized, which makes it possible to formulate optimization algorithm. The algorithm starts by placing the fireflies in random locations. The locations of a fireflies correspond to the values of the parameters for the objective function to be solved. The multiple objectives optimization problem in this research using FOA is implemented with the following steps (Yang, 2013):

1. Initializing number of fireflies, *n*, biggest attraction β_0, absorption coefficient of light intensity γ, step size factor α, and maximum number of iterations or generations t_{max}.
2. Initializing the positions of fireflies randomly, the values of objective functions of fireflies were set as their maximum brightness of fluorescence I_0.
3. Calculating relative brightness and attractiveness of fireflies belonging to the population. The direction of movement depended on the relative brightness of fireflies. An expression for this maximum brightness of fluorescence is (Yang, 2013):

$$I = I_0 \times e^{-\gamma rij} \quad (1)$$

$$\beta = \beta_0 \times e^{-\gamma rij} \quad (2)$$

where β_0 is the maximum attractiveness at $r = 0$, γ is the absorption coefficient of the light intensity, and r_{ij} is the spatial distance between fireflies *I* and *j*. The attractiveness of a firefly was proportional to its brightness and they both decreased with distance.

4. Updating the spatial positions of fireflies. Random perturbations were injected into the firefly with the best position. The updated equation is:

$$x_i = x_i + \beta \times (x_j - x_i) + \alpha \times (rand - 0.5) \quad (3)$$

where x_i, x_j represent the spatial positions of firefly *i*and *j*, respectively. α is the step size factor. *rand* is random factor distributed uniformly in [0,1].

5. Recalculating the brightness of fireflies according to the updated positions.
6. Returning to Step 3 until the search precision was met or the maximum number of generations was achieved.

The pseudo code of the FOA is given below (Yang, 2013).

Define objective functions $f_1(x)$, ..., $f_K(x)$ where $x= (x_1, ..., x_d)^T$
Generate initialize a population of *n*firefliesx_i $(i = 1, 2, ..., n)$.
Light intensity I_i at x_i is determined by $f(x_i)$.
Define light absorption coefficient γ.
while (*t*<MaxGeneration)
for *i* = 1: *n* (all *n* fireflies)
    for *j* = 1: *n* (all *n* fireflies) (inner loop)
    if $(I_i<I_j)$
        Move firefly *I* towards *j*.
    End if
    Vary attractiveness with distance r via exp[-γr^2]
    Evaluate new solutions and update light intensity.
    Enf for *j*
    End for *i*
    Rank the fireflies and find the current global best *g*.
    End while
    Processes results and visualization.

III. METHODOLOGY AND DESIGN PROCEDURES

The integrated filter and pulse amplifier design problem shown in Figure 4 is a continuous constrained problem. The problem is to maximize the mid-frequency of the band pass filter under abnormal heart beat conditions. The voltage signal at the output of the phototransistor contains a wide quasi DC signal (the extremely low frequency component). This DC signal arises by the average intensity of infrared signal, which reflected back from the tip of a finger. The essential reason for designing a high pass filter is to remove this DC signal. Since the heartbeat of an average healthy person ranges between 60 to 120 bpm, corresponding to 1 Hz – 2 Hz frequency range. In order to detect abnormal heartbeat conditions (30 bpm minimum or 210 bpm maximum), which again corresponds to a frequency rangesof 0.5 Hz and 3.5 Hzrespectively. This range of frequency is considered in this research. As a result, the passive high pass and active low pass filters should have a cutoff frequency of 0.5 Hz and 3.5Hz respectively, so as to attenuate any noise frequencies caused by ambient light and level detection distortions. The pulse amplifier gain is considered to be 100 (40 dB), while the active low pass filter gain is assumed to be 20 (26 dB). The optimization design circuit is presented in Figure 4.

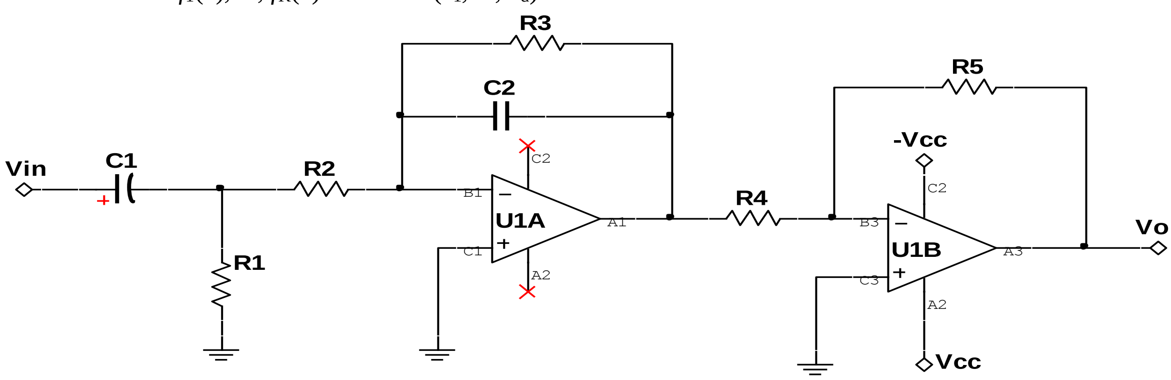

Fig.4: Schematic of Filter and Amplification System Design Problem

As shown in Figure 4, the coupling capacitor C1 together with resistor R1 forms a high pass filter which serves to attenuate the low frequency signals (degrading the low frequency heart beat signals) while allowing the high frequency signals. Capacitor C1 is also used as DC blocking to prevent immeasurable pulses caused by a high DC offset from the ambient light.The high pass filter with a cut-off frequency of 0.5 Hz is considered, since most of the motion artifacts signal is below this range of frequency. This high pass filter stage is next to the active low pass filter stage with a chosen cut-off frequency of 3.5 Hz. The modeling equations for the integrated BPF and pulse amplifier is presented as follows:

The HPF transfer function is calculated using equation (4):

$$H(s)_{HPF} = \frac{s}{(s+\omega_{c1})} \quad (4)$$

Where:

$$\omega_{c1} = \frac{1}{R_1 C_1} \quad (5)$$

The High Pass Filter (HPF) cut-off frequency is:

$$f_{HPF} = \frac{1}{2\pi R_1 C_1} \quad (6)$$

The LPF transfer function is therefore equal to:

$$H(s)_{LPF} = -G_1 \frac{\omega_2}{(s+\omega_{c2})} \quad (7)$$

Where:

$$\omega_{c2} = \frac{1}{R_3 C_2} \quad (8)$$

The Low Pass Filter (LPF) cut-off frequency is:

$$f_{LPF} = \frac{1}{2\pi R_3 C_2} \quad (9)$$

$$G_1 = \frac{R_3}{R_2} \quad (10)$$

The extracted signal is analysed by the pulse amplifier to providea pulse of high amplitude, which is required by the microcontrollerinput. The amplifier then detects the peak of each pulse and createsa corresponding pulse of high amplitude. This stage of thedesign requires that the amplified and filtered heart pulse signalhave a SNR of 66 dB to obtain a clean pulse of high amplitude.The time between each successive rising of high amplitudepulse edge is interpreted by the microcontroller as the periodbetween each heart pulse.To detect signal amplification, an LM358 operational amplifier is chosen and theheart signal is amplified onceafter passing through band passfilter (Figure 4). Finally, the amplified output that themicrocontroller needs as its input is obtained and calculates the heart rate. Therefore, the pulse amplifier gain G_2 is calculated as:

$$G_2 = \frac{R_5}{R_4} \quad (11)$$

Therefore, the Transfer Function for the Integrated Band pass filter and the pulse amplifier is found to be:

$$\frac{V_0}{V_i} = \left(\frac{s}{s+\omega_{c1}}\right)\left(\frac{-G_1\omega_{c2}}{s+\omega_{c2}}\right)\left(-\frac{R_5}{R_4}\right) \quad (12)$$

That is

$$H(s) = \frac{s(G_1 G_2 \omega_{c2})}{(s+\ \omega_{c1})(s+\ \omega_{c2})} \quad (13)$$

The system gain in decibel is:

$$A_{dB} = 20\log_{10}|H(j\omega)| \quad (14)$$

The filter mid-frequency f_m is found as:

$$f_m = \sqrt{f_{lower} * f_{upper}} \quad (15)$$

Where:

f_{lower} is the HPF cut-off frequencyf_{HPF} and f_{upper} is the LPF cut-off frequency f_{LPF}.

As shown in Figure 4, the problem consists of seven design variables which are:

High pass filter resistor R1 = $x_1 \in [1\times10^3, 1\times10^4]$;
Low pass filter resistor R2 = $x_2 \in [1\times10^3, 5\times10^4]$;
Low pass filter resistor R3 = $x_3 \in [2\times10^4, 6\times10^5]$;
Amplifier gain resistor R4 = $x_4 \in [1\times10^3, 1\times10^4]$;
Amplifier feedback resistor R5 = $x_5 \in [1\times10^4, 1\times10^6]$;
High pass filter capacitor C1 = $x_6 \in [1\times10^{-6}, 1\times10^{-4}]$;
Low pass filter capacitor C2 = $x_7 \in [1\times10^{-9}, 1\times10^{-7}]$;

The mathematical formulation of the Band pass filter and amplifier design problem is as follows:

$$\min f(x) = \sqrt{f_{lower} * f_{upper}} \quad (16)$$

Subject to

$$q_1(x) = 15 - \frac{x_3}{x_2} \leq 0 \quad (17)$$

$$q_2(x) = \frac{x_3}{x_2} - 25 \leq 0 \quad (18)$$

$$q_3(x) = 100 - \frac{x_5}{x_4} \leq 0 \quad (19)$$

$$q_4(x) = \frac{x_5}{x_4} - 150 \leq 0 \quad (20)$$

$$q_5(x) = 0.5 - \frac{1}{2*pi*x_1*x_6} \leq 0 \quad (21)$$

$$q_6(x) = \frac{1}{2*pi*x_1*x_6} - 1 \le 0 \qquad (22)$$

$$q_7(x) = 2.5 - \frac{1}{2*pi*x_3*x_7} \le 0 \qquad (23)$$

$$q_8(x) = \frac{1}{2*pi*x_3*x_7} - 5 \le 0 \qquad (24)$$

The design problem upper and lower bounds variables are:

$$1\times10^3 \le x_1 \le 1\times10^4 \quad 1\times10^3 \le x_2 \le 5\times10^4 \quad 2\times10^4 \le x_3 \le 6\times10^5$$

$$1\times10^3 \le x_4 \le 1\times10^4 \quad 1\times10^4 \le x_5 \le 1\times10^6 \quad 1\times10^{-6} \le x_6 \le 5\times10^{-4}$$

$$1\times10^{-9} \le x_7 \le 1\times10^{-7} \qquad (25)$$

IV. RESULTS AND DISCUSSIONS

In this research, the integrated band pass filter and pulse amplifier design problem was solved using FOA. In order to converge to the optimum point, the program took 20 fireflies, and 25 iterationsalong with randomness factor,α = 1, attractiveness of a firefly, β = 0.2 and Absorption coefficient, Ω = 1. Table1 contains histories of design (Input) variables (high pass filter resistor R1, high pass filter capacitor C1, active low pass filter resistor R2, active low pass filter feedback resistor R3, Active low pass filter capacitor C2, pulse amplifier input resistor R4 and pulse amplifier feedback resistor R5)and the objective function (BPF mid-frequency). The initial objective is to obtaincomplete integrated band pass filter and the pulse amplifier system for reducing the effects of motion artifacts in cardiac rate measurements.Table 1 presents the history of the objective functionfrom the total of 25 accepted iterations.

Table 1. Iterative Optimization Simulation Process for Integrated BPF and Pulse Amplifier Design using FOA

Iter.	Input Variables							Output
	R1 (x_1) (kΩ)	R2 (x_2) (kΩ)	R3 (x_3) (kΩ)	R4 (x_4) (kΩ)	R5 (x_5) (kΩ)	C1 (x_6) (µF)	C2 (x_7) (nF)	Obj. Fun. (Hz)
1.	6.87634	22.44101	484.12261	8.76601	831.53057	39.38715	78.91876	1.5646
2.	6.87634	22.44101	484.12261	8.76601	831.53057	39.38715	78.91876	1.5644
3.	6.87634	26.31365	390.61537	6.02322	608.96541	20.94411	93.16974	2.1984
4.	4.60542	24.85066	494.27394	6.34280	647.34586	35.73467	78.58205	1.9907
5.	7.82198	24.85066	494.27394	6.34280	647.34586	35.73467	78.58205	1.5275
6.	7.82198	24.85066	494.27394	6.34280	647.34586	35.73467	78.58205	1.5275
7.	7.82198	24.85066	494.27394	6.34280	647.34586	35.73467	78.58205	1.5275
8.	7.82198	26.66778	502.60259	6.84515	726.73493	23.87128	85.51119	1.875
9.	6.49999	25.23985	509.60825	7.03947	725.87979	27.70253	80.72953	1.8489
10.	6.49999	25.23985	509.60825	7.03947	725.87979	27.70253	80.72953	1.8489
11.	6.95616	26.37132	507.85094	6.83393	745.09791	25.23917	84.19433	1.8367
12.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
13.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
14.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
15.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
16.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
17.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
18.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
19.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
20.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
21.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
22.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
23.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175
24.	6.78852	25.81101	506.71717	6.95425	740.96199	27.00460	82.52837	1.8175

25.	6.77511	25.77881	507.03357	6.96300	739.83701	27.04945	82.50568	1.8175

The oscillatory plot of the 25 iterations is presented in Figure 5. Oscillatory trend in the iterative process is due to the randomization parameter of the FOA, which eventually caused the variations in the design variables as the iterations progress.

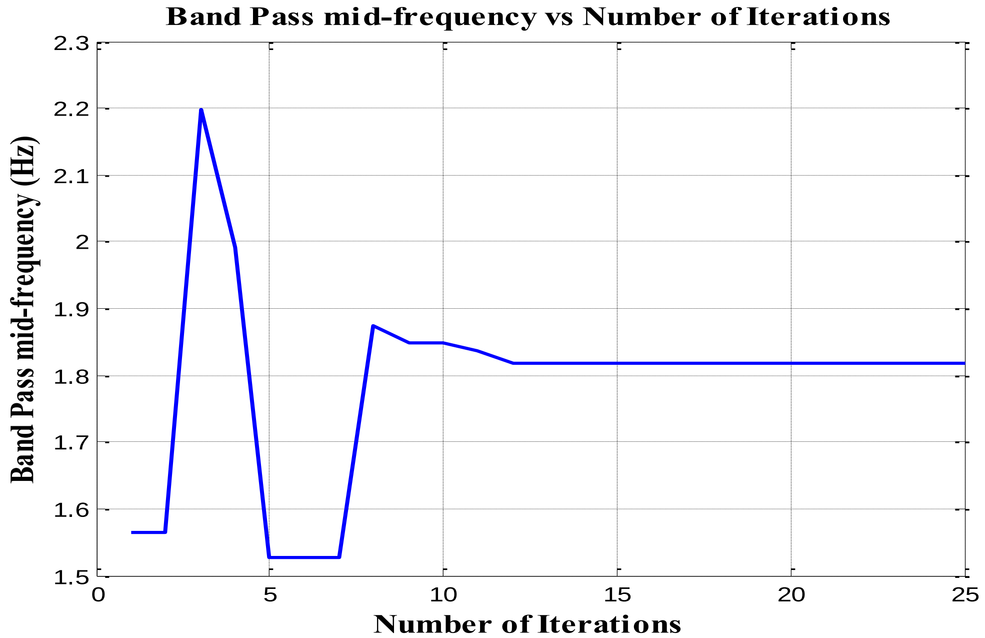

Fig.5: The Plots of BPF mid-frequency versus Number of Iterations

As seen in Figure 5, oscillations were observed in the objective function (output) with the initial iterations before remaining almost constant. This is an indication that the band pass filter mid-frequency reduces with increasing parameters ofeither the low pass filter or high pass filter. It was further observed that the relationship between the band pass filter circuit elements and the mid-frequency of the BPF is inversely proportional. Also, for the active low pass filter, increase in feedback resistor decreases the cut-off frequency while increasing the filter gain.The best optimalFOA design of the BPF and pulse amplifier parameters is the mid-frequencylisted in the iteration number 25 of Table 1, which has the following technical characteristics presented in Table 2.

Table 2: Optimum Results for the Integrated BPF and Pulse Amplifier Optimization Design with FOA

Input Variables	**FOA design values**	**Reference Parameters**	**Unit**
High pass filter resistor, R1	6.7751	-	kΩ
High pass filter capacitor, C1	27.0494	-	µF
Active low pass filter resistor, R2	25.7788	-	kΩ
Active low pass filter feedback resistor, R3	507.0336	-	kΩ
Active low pass filter capacitor, C2	82.5057	-	nF
Pulse amplifier input resistor, R4	6.9630	-	kΩ
Pulse amplifier feedback resistor, R5	739.8370	-	kΩ
Output Characteristics	**FOA design values**	**Reference Parameters**	**Unit**
Active Low Pass filter Gain, G1	19.6686	20	-
Pulse Amplifier Gain, G2	106.2525	100	-
High pass filter cut-off frequency, □□□□□□	0.86845	0.5	Hz
Corresponding Heart rate for □□□□□□	52	30	BPM
Active low pass filter cut-off frequency, □□□□□□	3.80452	4.0	Hz
Corresponding Heart rate for □□□□□□	248	240	BPM
Band pass filter Mid-frequency	1.8175	2.0	Hz

BPF and pulse amplifier overall gain	2089.7772	2000	-
BPF and pulse amplifier overall gain	66.402	66.02	dB
BPF and pulse amplifier sensitivity @ 2.5mV input	5.224	5.00	V

As seen in Tables 2, the optimum solution has a lower and upper cut-off between 0.86 Hz and 3.8 Hz, which correspondsto heartbeat in the range of 52 -248 bpm with a gain of 2089.7772 (66.4dB), which again corresponds to 5.224V output voltage from the complete system. This implies that, with a specific variation of the values of the integrated BPF and pulse amplifier, a higher sensitivity and lower cut-off frequencies is possible. Therefore, after having considered the standard values of resistors and capacitors for the circuit simulations in this research, the electronic circuitsweresimulated by using National Instruments Multisim 11 software. The complete schematic diagram of the simulated BPF and pulse amplifier with standard values of electronics circuit elements is presented in Figure 6 with the performance characteristics shown in Table 3.

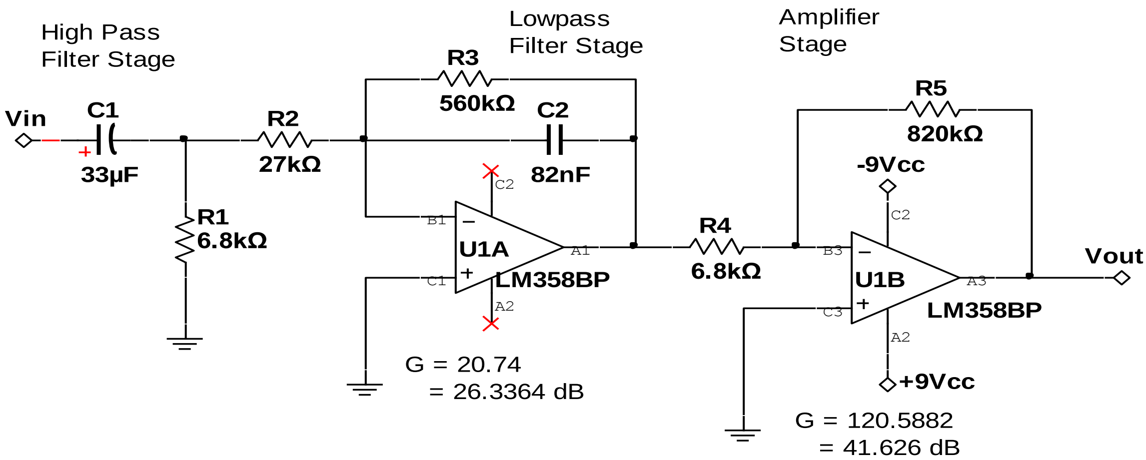

Fig.6: Complete BPF and Pulse Amplification Schematic

Table 3: Comparison of FOA Optimum and Circuit SimulationResults

Parameters	**FOA Design**	**Simulated HBM with standard values**	**Unit**
Lower cut-off frequency	0.86	0.70	Hz
Upper cut-off frequency	3.80	3.46	Hz
Overall gain	1620	1988	-
Overall gain	64.19	65.969	dB
Output Voltage @ 2.5mV input	4.0489	4.9704	V

As shown in Table 3, the performance of the complete heartbeat sensor circuit is tested and analyzed. The lower and upper cut-off frequencies of the simulated BPF and pulse amplifier circuit were found to be 0.7 Hz and 3.46 Hz which corresponds to 42 bpm and 207 bpm respectively.By evaluating the sensitivity of the designedheartbeat monitor, the measured maximum output voltageis found to be 4.97 V. In order to determine the corresponding heartbeat rateof the lower and upper frequencies, the sensor frequencies aremultiplied by the maximum seconds per minute as:

□□□ = □□□□□□□□□ × 60 (26)

From Table 3, significant reduction in lower cut-off frequency obtained from the high pass filter and upper cut-off frequency obtained from the low pass filter are achieved with the simulated FOA designed cardiac rate monitor. Most importantly, there is significant increase inoutput voltageand reduction in motion artifact effect as observed from the lower cut-off frequency of the high pass filter.

V. CONCLUSION

The possibility of applying metaheuristic optimization algorithm, especially firefly optimization algorithm, for finding the optimal values of the integrated band pass filter and pulse amplifier simultaneously has been demonstrated in this research. Integrated band pass filter and pulse amplifier design is a complex task that includes many variations in design variables so as to minimize the effect of motion artifacts and satisfying cardiac rate measurements (specifications) with respect to power consumption and temperature stability. The efficiency of the proposed cardiac rate monitor design optimization algorithm is presented through circuit simulation.The FOA design results indicated that the lower frequency, upper frequency, and the gain of the whole system are 0.86 Hz, 3.8 Hz, and 64.19 dB respectively, which corresponds to heartbeat in the range of 52 bpm to 228 bpm at a maximum voltage of 4.08V. In order to verify the validity of the FOA design, a prototype sensor has been simulated in National Instrument Multisim 11 Software, and the simulation frequency (lower and upper cut-off frequencies) and sensitivityresponses are0.7 Hz, 3.4 Hz, and 66 dB respectivelywhich corresponds to heartbeat in the range of 42 bpm to 207 bpm at a 4.97V maximum voltage.

The results obtained so far clearly shows the effectiveness of the firefly optimization algorithm as a better solution to cardiac rate optimization design problems.The Firefly algorithm having the advantages such as less computation time, avoid heavy computation of design process, and high quality solution. It is significant that firefly optimization algorithm can be effectively used to optimize the electronics design problems.

VI. REFERENCES

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