5-3-2024

Real-time Analysis of Photoplethysmogram and Electrocardiogram for Assessment of Physiological Correlates of Attention

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Real-time Analysis of Photoplethysmogram and Electrocardiogram for Assessment of Physiological Correlates of Attention

by

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An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

to

The Honors College

of

The University of Alabama in Huntsville

May 3, 2024

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Abstract:

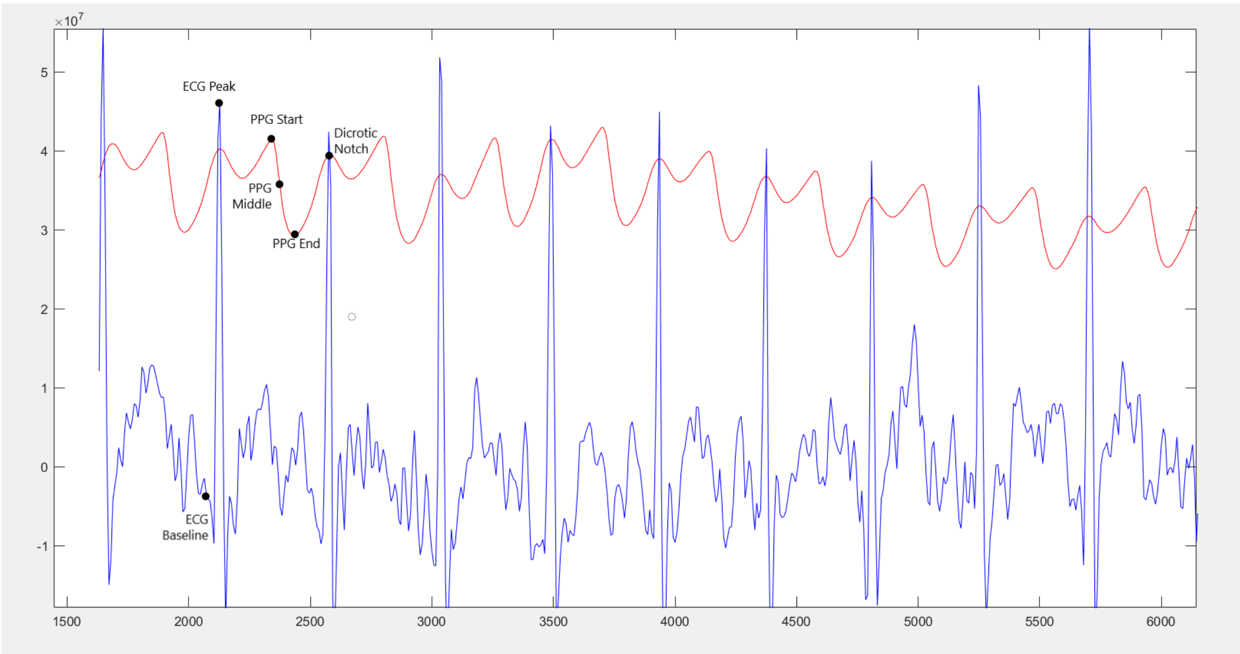
Improvement of human attention and cognitive function can provide many benefits to psychological tasks. This project aims to create a non-invasive method of estimating heuristics for attention and cognitive effort via the use of Photoplethysmogram (PPG) and Electrocardiogram (ECG) devices. These two non-invasive devices which monitor heart activity can be used to observe and estimate several characteristics of the physiological state of a user, which can be used for monitoring and to provide feedback to the user via the Attention Monitoring and Cognitive Enhancement System (ACES).

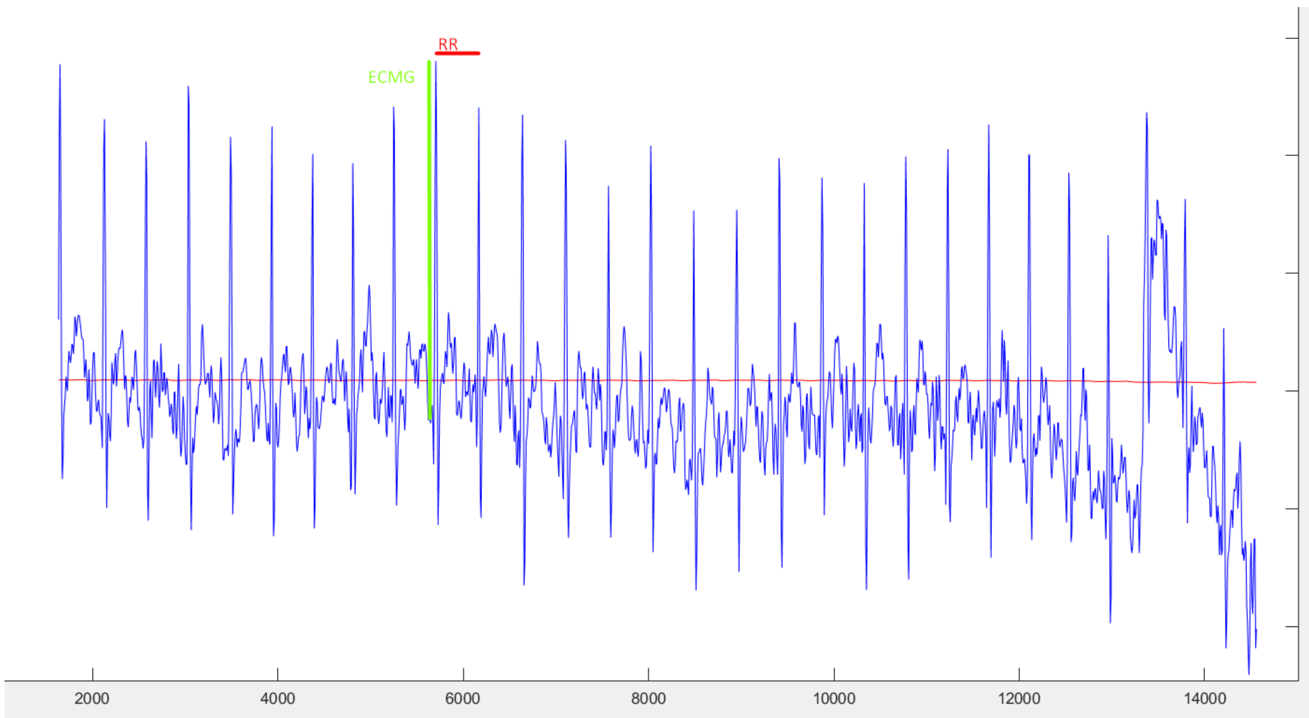
Thesis:

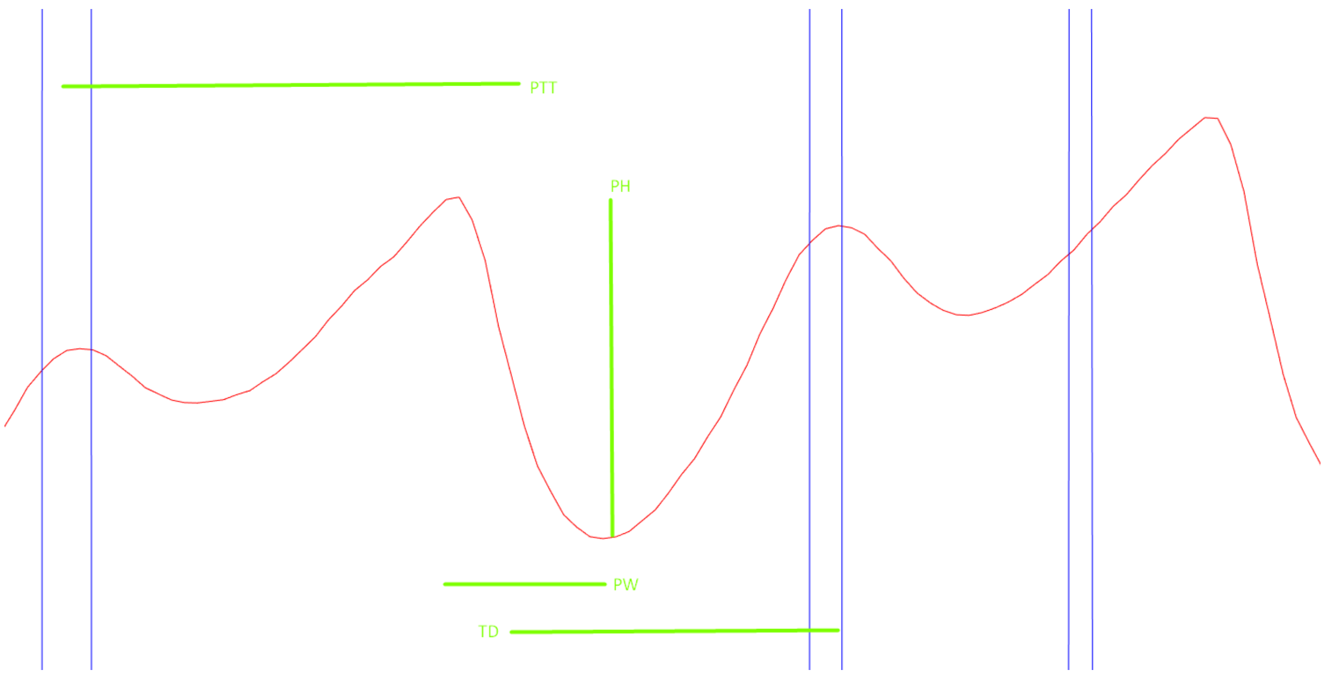
Research has shown that PPG and ECG signals can be combined in analysis to estimate several factors that are indicative of a user's current stress and cognitive effort. Hosseini and Lowe were able to use these signals and their characteristics to create a convolutional neural network that was able to estimate blood pressure, a common metric of stress, within a small and acceptable margin of error. This is just one of the ways these signals can be analyized when combined with each other, with many more that can be explored.

Given the importance of these two symbols combined, it is essential to have a system that can not only record these measurements but also calculate several defining characteristics of the signals in real time so that these process can be applied while a user is actively connected to the system rather than as post-operational analysis. The key characteristics I have discovered for this analysis are the following: the difference in time between an ECG peak and the following PPG pulse's middle known as Pulse Travel Time (PTT), the difference in time between subsequent peaks of ECG pulses which is known as the R-Wave Interval (RR), the relative magnitude of an ECG pulse, the height and width of a PPG pulse, and the difference in time between the middle of the previous PPG pulse and the peak of the subsequent dicrotic notch known as Dicroitc Notch Latency (TD).

These following plots demonstrate the characteristics that are being identified based on the plot of the raw ECG and PPG data. The blue line is the ECG signal and the red line is the PPG signal. In the first graph the PPG signal has been scaled up and shifted vertically for better presentation of information.







To perform the analysis required to gather these data points in real time, I implemented a real-time filter developed by Svitzky and Golay on incoming data that was able to give the derivative of a smoothed version of the raw signal. This filter is extremely fast and efficient in calculating this derivative, requiring only a window size of 5 and with only integer coefficients. Through the use of this filter I was able to locate the peaks, valleys, and middle of the PPG signal in real time with only a delay of two samples, which at the current sample rate is only a total delay of 16ms, which can be accounted for when recording the data.

The data gathering, filting, and calculations are being conducted on a HealthyPi v5 board with its provided PPG finger sensor and ECG electrodes. This device significantly expedited development process as it was already designed to gather the raw data that this project uses, so it was only the filtering and analysis that needed to be constructed as additional programming. The algorithm has been developed both in C for real-time operation on the HealthyPi board as well as in Python for post-operational analysis on data that was gathered before the implementation of the C program.

The data filtering and gathering is fully implemented onto the HealthyPi. The different values are all sent over USB communication to a receiver program once every heartbeat. The RR values recorded can be used to estimate heartrate in real time as they are inversely proportional to each other. PTT and TD are both able to be combined to estimate blood pressure as Hosseini and Lowe were able to accomplish with their neural network. These characteristics can be used via a researcher or neural network created by a researcher in tandem with the other recorded characteristics to analyze a patient's physiological state in ways that are outside the scope of this project and my research. The following code is the operation of the algorithm on the HealthyPi board.

```
sendFlag = false;

  ecgWindow[0] = ecgWindow[1];
  ecgWindow[1] = ecgWindow[2];
  ecgWindow[2] = ecgWindow[3];
  ecgWindow[3] = ecgWindow[4];
  ecgWindow[4] = ecg_sample;

//Finds the peaks of ECG signal.
  if (ecgWindow[2] <= ecgWindow[3] && ecgWindow[4] <= ecgWindow[3] &&
ecgWindow[3] >= 20000000) {
    RR = 8*((sampleCount - 1) - ecgPeak);
    ecgPeak = sampleCount - 1;
    ECMG = ecgWindow[3] - ecgWindow[0];
  }

  ppgWindow[0] = ppgWindow[1];
  ppgWindow[1] = ppgWindow[2];
  ppgWindow[2] = ppgWindow[3];
  ppgWindow[3] = ppgWindow[4];
  ppgWindow[4] = ppg_sample;

//This filter finds the derivative of the smoothed curve of the PPG
signal for t = -2
//As such filteredWindow[2] refers to the derivative at the same time as
ppgWindow[2] not ppgWindow[4]
  filteredWindow[0] = filteredWindow[1];
  filteredWindow[1] = filteredWindow[2];
  filteredWindow[2] = -2 * ppgWindow[0] - 1 * ppgWindow[1] +
ppgWindow[3] + 2*ppgWindow[4];
```

```
//Finds local minima of certain magnitude for the derivitive to
determine where the PPG pulse's slope is the most negative.
//This gives an estimate for the middle of the PPG pulse.
  if (filteredWindow[1] <= filteredWindow[0] && filteredWindow[1] <=
filteredWindow[2] && filteredWindow[1] <= -40000){
    dFlag = true;
    pulseMid = sampleCount - 3;
    PTT = 8*((sampleCount - 3) - ecgPeak);
  }
//Find where the derivative goes from negative to positive. This
correlates to the valleys in the PPG signal.
  else if (filteredWindow[1] <= 0 && filteredWindow[2] >= 0){
    //If the flag is set then this is the pulse minimum value.
    if (dFlag){
      PW = 8*((sampleCount - 2) - pulseStart);
      PH = pulseMagMax - ppgWindow[2];
    }
  }
//Find where the derivative goes from postivie to negative. This
correlates to the peaks in the PPG signal.
  else if (filteredWindow[1] >= 0 && filteredWindow[2] <= 0){
    //If the flag is set then this is the dicrotic notch peak.
    if (dFlag){
      dFlag = false;
      TD = 8*((sampleCount - 2) - pulseMid);
      sendFlag = true;
    }
    //If the flag is not set then this is the pulse maximum value.
    else{
      pulseStart = sampleCount-2;
      pulseMagMax = ppgWindow[2];
    }
  }
```

This is called every 8ms for a sample rate of 125Hz on the PPG and ECG, keeping a window of previous values for analysis, performing the filtering required to find the derivative of the PPG signal, and then executing the analysis of that derivative to determine the location of key points used to determine the output values. All variables besides flags and the sampleCount are 32-bit signed integers, which are booleans and a 32-bit unsigned integer respectively. Afterwards if sendFlag is set then the data is compiled into a packet and sent via USB serial.

This sample of recorded data shows the format that is output by a Python script reading the values sent over USB serial communication from the board. The data packets are sent as a 5 byte header, a 28 byte data segment, and a two byte footer. Each 4 bytes of the data segment comprises one of the following 32-bit numbers, which are broken down into bytes for transmission over the wire. Information on the header and footer can be

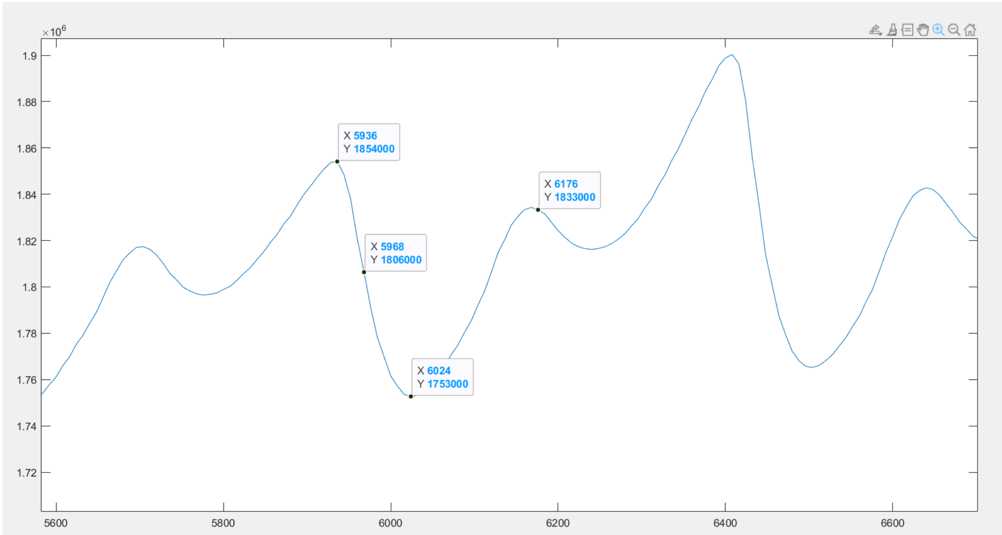
```
Tms, RR, ECMG, PTT, PW, PH, TD
1080, 600, 58720258, 496, 120, 51692, 232
1368, 600, 58720258, 280, 528, 133241, 136
1648, 56, 66519043, 464, 664, 258463, 232
1960, 56, 66519043, 184, 1064, 171913, 216
2208, 616, 68485119, 432, 1256, 215978, 216
2784, 200, 63504387, 0, 128, 53709, 216
3344, 56, 67502082, -16, 120, 52361, 216
3880, 64, 59506690, 16, 120, 50475, 224
4424, 344, 65929219, 152, 112, 50379, 224
4992, 376, 66191359, 192, 104, 48892, 224
5608, 616, 75169791, 424, 104, 50474, 232
6336, 728, 67633152, 528, 112, 53798, 240
7104, 760, 63111171, 568, 112, 56190, 240
7792, 696, 69926909, 512, 112, 47952, 224
8424, 632, 64618497, 456, 120, 52281, 216
9016, 592, 64552961, 416, 120, 51710, 216
9584, 560, 71237632, 376, 112, 50381, 232
10136, 560, 70713344, 368, 112, 47277, 232
10736, 600, 74579970, 416, 112, 47294, 224
11408, 672, 75497472, 488, 104, 45936, 224
12104, 696, 55836669, 520, 104, 43910, 216
12776, 672, 70057984, 488, 104, 40317, 224
13392, 600, 55181312, 432, 112, 37887, 224
13936, 544, 41746434, 384, 112, 34404, 216
16960, 824, 37421058, 648, 88, 28760, 248
```

The program has been validated by recording its data alongside raw recordings of the PPG and ECG signals and manually anylizing beats via Matlab plotting to determine any errors generated by the program. The following is the validation process for a single heartbeat. This is done using a different C and Python program that outputs the sample and characteristic values for every sample rather than every heartbeat.

1) Zoom in on two subsequent PPG pulses.

2) Locate the absolute peak of the first pulse, absolute valley of the first pulse, and the dicrotic notch following that valley.

3) Estimate the midpoint of the first PPG pulse.

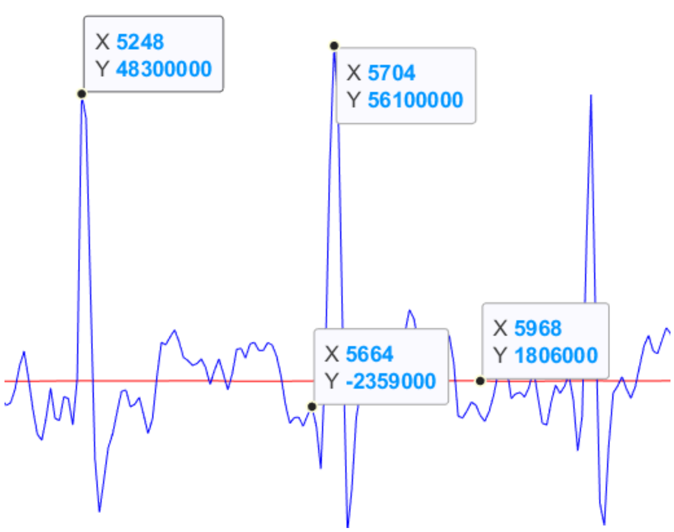


4) Calculate the characteristics that are solely based on PPG signal and compare them to what the program listed at the time of the dicrotic peak + two sample rates to account for the delay in processing caused by the filter.

Characteristic	Manual Observation	Program Output
PW	88	96
PH	101000	100959
TD	208	208

As you can see first two values are slightly off while the TD is exactly as the program output. This is likely to me selecting a peak value one sample off from what the algorithm estimated, but is easily within acceptable error.

5) Unselect all your points except the midpoint and zoom out to select a the peak and a baseline value from the ECG spike before that PPG pulse as well as the peak from the previous ECG pulse before that. Use the program's values from the same timestamp.



6) Repeat your analysis as done earlier.

Characteristic	Manual Observation	Program Output
RR	456	464
ECMG	58459000	57671681
PTT	264	264

The values are once again extremely similar with any error likely due to slightly altered point selection. The magnitude is within a 1.35% error.

7) This process can be repeated, and was during testing, to ensure the program's validity.

These results show that this program and hardware are a capable method of calculating these essential characteristics from a user in order to provide non-invasive monitoring of their physiological state in real-time.

I did not accomplish as much as I would have liked throughout this project. I would've liked to have actually implemented the blood pressure and cognitive effort estimations in my programs, but I was unable to get a strong enough grasp on both the artificial intelligence and the biological aspects required to develop such an algorithm. This project can be used as the cornerstone of such a future project as it provides all the required datapoints that can be analyized going forward. It also will be usable for refinement of the ACES which was the senior design project this project was a component of and which seeks to use this data to provide stimulation to a user to improve their performance in cogntivite tasks.

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Abraham. Savitzky and M. J. E. Golay
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S. Rastegar, H. Gholam Hosseini, and A. Lowe, "Hybrid CNN-SVR blood pressure estimation model using ECG and PPG Signals," MDPI, https://doi.org/10.3390/s23031259 (accessed Feb. 29, 2024).

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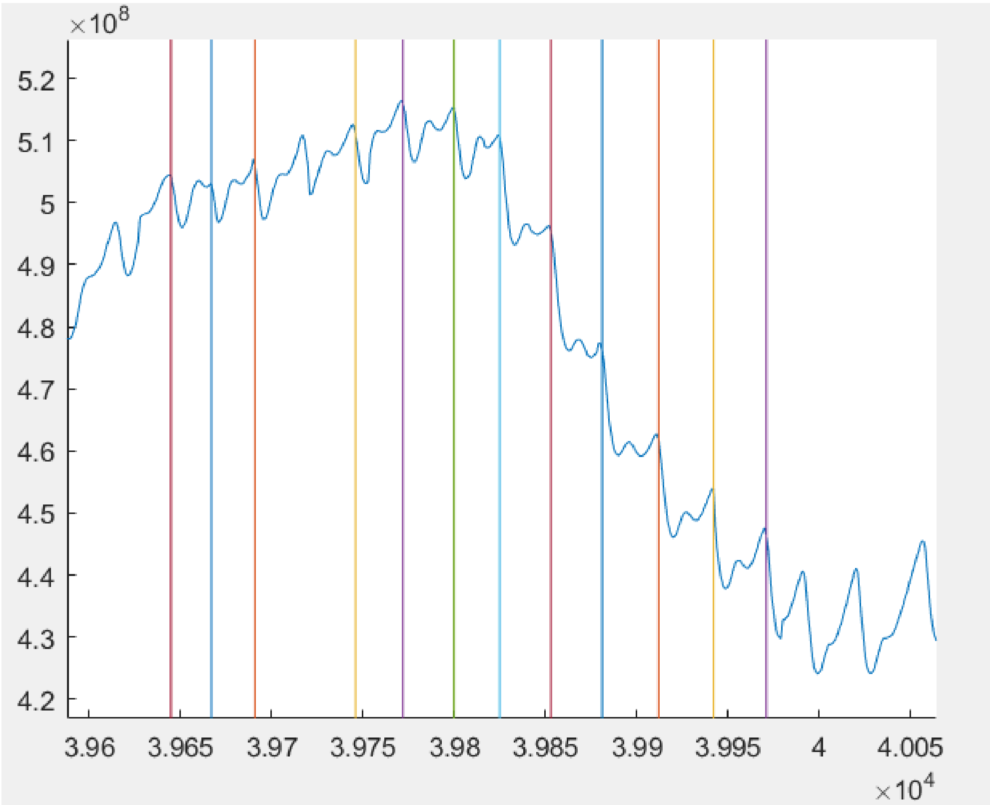
Tables and Graphs:

A Matlab implementation of the algorithm used to determine the peaks of PPG signals:



A sample of recorded values from the program running over the course of a couple minutes.