A Complete Set-up to Evaluate the Correlation Between Blood Pressure and Pulse Transit Time

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Abstract— **Blood pressure (BP) has always been one of the most important parameters in monitoring cardiovascular system conditions and coronary artery diseases (CAD), such as angina and myocardial infarction (commonly known as a heart attack). This is due to the fact that many of the changes within the cardiovascular system, such as clogged arteries, for example, are reflected by changes in BP. A number of methods and devices that can measure BP are available on the market for both clinical and consumer use. However, being able to measure one's own BP non-invasively, with the required frequency (even continuously) in a comfortable fashion remains an unsolved problem using currently available systems. To date, the Pulse Transit Time (PTT) measurement method has been seen as a feasible approach to help bring current blood pressure monitoring systems to a stage where non-invasive, continuous measurements are viable. However, developing a system which uses the PTT method for blood pressure measurement is as yet an unsolved problem and it remains a challenge to achieve accurate BP results despite considerable research in the past decade. In this paper, we present the first step in building a smart sensing system that overcomes the technical difficulties associated with accurate measurement of PTT. The novel hardware developed incorporates multi-modal sensing capability to explore and quantify the relationship between blood pressure and PTT. The evaluation system is completed by efficient, simple and fast embedded software algorithms, user interface, and clinical validation trials that will enable delivering a novel PTT-based blood pressure monitor.**

Keywords - blood pressure; pulse transit time; ECG; PPG; calibration; real time data; clinical trials.

I. INTRODUCTION

According to statistics, cardiovascular diseases (CVD) are the main cause of deaths in Europe with 45% of all deaths caused by CVDs [1]. The overall estimated cost to the EU economy is €210 billion a year [2]. The motivation for this research is to reduce these statistics by finding an improved method of continuously monitoring real time blood pressure (BP). This will help clinicians to monitor, diagnose and improve the condition of the cardiovascular system [3] through the availability of more detailed real time data sets.

The current state of the art in BP measurement utilises a number of different methods and devices including catheterization, auscultation, oscillometry, volume clamping, and tonometry, with catheterization being the most accurate standard currently being used [4]. In general, the accuracy of the measurements obtained by existing devices is acceptable, but they have a number of drawbacks. Firstly, where inflatable cuffs are used, they tend not to be comfortable for the user and as a result are inappropriate for long term continuous monitoring. Secondly, clinical grade systems need to be operated by doctors, which causes a phenomenon called 'white coat syndrome', where BP readings are inaccurate due to the presence of the clinicians.

A system which would enable clinicians to take accurate, real time and continuous BP measurements would be invaluable to doctors in diagnosing CVDs at an early stage [3].

In this paper, the first development stage of such a system for BP monitoring based on the PTT method is presented. Section II of this paper describes the principles behind the PTT measurement method. Section III describes the evaluation of components integrated into the system hardware platform and the design of a custom hardware and new sensors.

Sections IV and V describe the developed embedded software and user interface respectively. The experimental protocol which was developed in conjunction with clinical inputs and which was used in the validation trials and the associated measurements taken from the subjects as well as the initial processed results are shown in Section VI. Section VII presents the second design phase of the final device which is currently underway. Finally, Section VIII concludes the work with some preliminary test results and a description of future work to be undertaken.

II. PULSE TRANSIT TIME

A method that proposes to have a good potential to enable non-invasive continuous BP measurement is the Pulse Transit Time method. PTT is defined as the time needed for the blood wave that goes out of the heart with each beat to arrive at a peripheral body site, in our case the wrist or fingertip. The delay (PTT) is calculated as the time difference between the peak of electrocardiograph (ECG) and the peak of photoplethysmogram (PPG) signals.

The main factors that determine the speed of propagation of the pulse wave, and which thus affect the PTT value, are the elasticity coefficient, the thickness of the arterial wall, the

end-diastolic diameter of the vessel lumen and blood density [5]. In 1878, Moens and Korteweg developed a formula that relates the velocity of the pulse with the factors as described in (1):

$$PWV = \frac{D}{PTT} = \sqrt{\frac{tE}{\rho d}} \quad (1)$$

The Pulse Wave Velocity (PWV) is dependent on a number of arterial properties, namely the elasticity of the artery wall E, the arterial wall thickness t, the arterial diameter d and the density of the blood ρ [6]. So, as the density of blood is close to that of the density of the water, the main factors that influence the velocity of the pulse wave are the properties of the arterial vessels, stiffness and thickness. These factors vary from person to person on an individual basis [5]. In the calculation of BP parameters from PTT readings for an individual, this variation would be addressed through a calibration activity as part of the measurement protocol, but this is insufficient, as vessel properties keep changing in a dynamic fashion due to a variety of factors [7]. Factors that can change vessel properties include ambient temperature [8, 9] barometric pressure [10], sleep-wakefulness status of the person [11], time of the day [12], sport activities [13] and sometimes it can even change by the control of the brain or sympathetic system [14].

III. TYNDALL PTT EVALUATION SYSTEM

In order to evaluate the impact of the variability inducing factors described above in the evaluation of BP and blood vessel properties, the WSN group at Tyndall has developed novel multi modal sensing system with the required hardware, sensors and algorithms, to be able to carry out the necessary measurements. The first implementation of the measurement system is shown in Figure 1.

A. Microcontroller Hardware System Design

The focus of this system implementation is the development and test of a smart sensing device in the form factor of a wrist watch, which would include the processor, battery, data visualisation interface, communications and all sensors required to measure BP using the PTT method.

To achieve this, our design methodology had to focus on three main parameters. Firstly, the size of the components should be small enough to fit in our miniaturised target device. Secondly, the microcontroller (MCU) should be powerful in its operations, as it will be a real time data acquisition system and it will run all the algorithms inside the embedded microprocessor. And thirdly, it should be a system that spends as little energy as possible as it is battery operated.

Considering all these parameters, we have chosen the STM L series microcontrollers [15] to use as a computing unit.

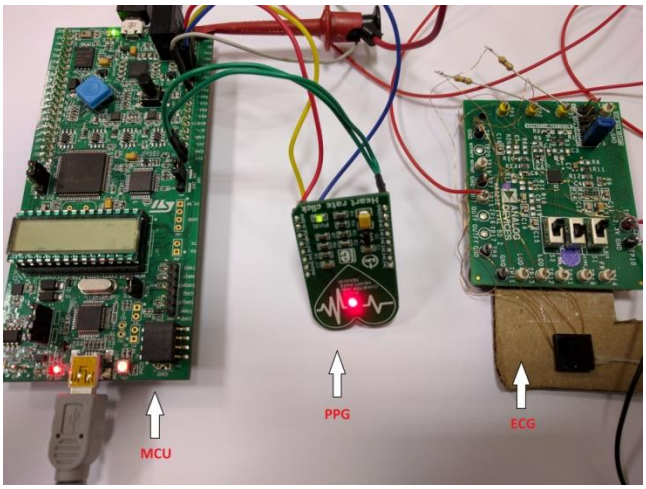

Figure 1. Setup of the evaluation board prototype data acquisition system.

As this device is a 32-bit microprocessor that can run at clock speeds of up to 100 MHz, it will satisfy our computing needs from an algorithmic perspective. At the same time, size-wise the STM component is small enough to fit inside a smart watch form factor system and is one of the lowest energy consuming microcontrollers on the market, if embedded code is managed appropriately. In addition to the before mentioned performance characteristics of the STM component, the MCU is also required to have a powerful Analog to Digital converter (ADC) and other digital interfaces to read data from the chosen sensors. Figure 1 shows a picture of evaluation boards that we are using as a first data acquisition prototype. The board on the left is the evaluation board with the STM microcontroller MCU.

B. ECG and PPG sensors

To develop the necessary algorithms to calculate PTT, it is anticipated that we will need to have datasets associated with two signals associated with the cardiovascular system. The heart, during work activities, generates a bio-signal that is well known and characterised as ECG, this is one of the waveforms we need to establish our BP measurement algorithm. Generally, these signals are recorded by placing electrodes on the skin, on the chest area, where the signals are stronger. Reading ECG by placing electrodes on the chest, gives the strongest and most easily read signal, but in general, this is not comfortable and convenient for the user. For the Tyndall ECG measurement system, we will use two active electrodes, which are placed in the watch in a wrist mounted implementation.

The sensor used for this application is named the Electric Potential Integrated Circuit (EPIC) from Plessey Semiconductors [16]. The EPIC sensor can be used, as a replacement technology for traditional wet-electrode ECG pads, because it requires neither gels nor other contact-enhancing substances. When the EPIC sensor is placed on (or in close proximity to) the patient, an ECG signal can be recovered.

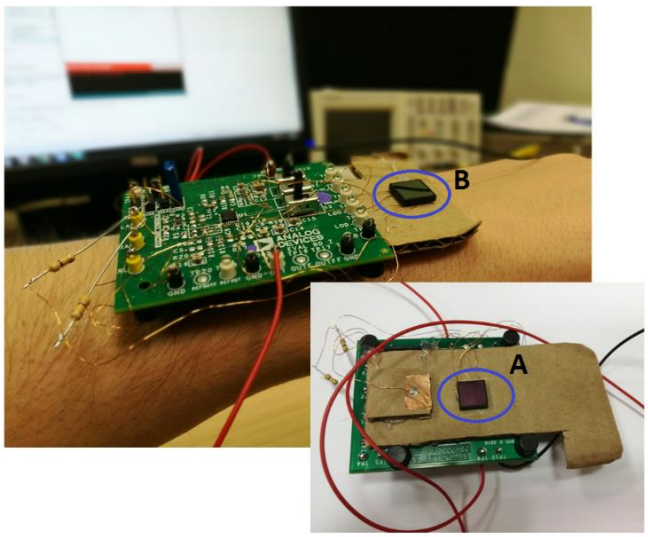

Figure 2. Evaluation board of ECG sensor.

To illustrate the placement of the electrodes to enable ECG measurements, consider Figure 2, where we show the development board of ECG sensor placed on a subject's wrist (electrodes in contact with the skin on the underside of the board as shown in the smaller picture). To enable ECG measurement in the wrist mounted scenario, there are two electrodes, electrode A and B. Electrode A is placed under the watch and will touch the skin. Electrode B is placed over the watch, so every time the user wants to measure BP, the user should touch electrode B with a finger of the opposite hand to read the differential signal. Figure 3 shows the differential amplifier which enables generation of the differential bio-signal. Input1 is the electrode touching the skin on the wrist and Input2 is the electrode touched by the finger of the opposite arm.

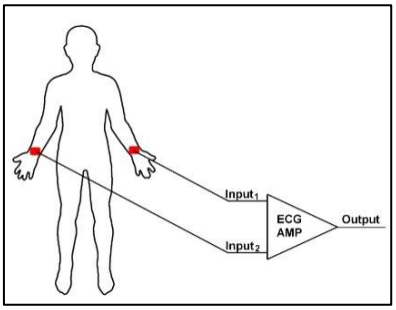

Figure 3. Generating differential biosignal from two inputs

The second waveform that is needed to develop the BP measurement algorithm is the signal generated from a photoplethysmogram (PPG) sensor, which shows the level of the volume of blood circulating near the sensor. The system used in the Tyndall implementation is a Maxim PPG sensor, MAX30100 [reference], which contains two light-emitting diodes (LED), one red and the other one is infrared together with a photodiode.

The change in volume caused by the pressure pulse is detected by illuminating the skin with the light from a LED and then measuring the amount of light either transmitted or reflected to a photodiode. Each cardiac cycle appears as a peak, as seen in Figure 7.

We are using this sensor to read PPG data from the fingertip, which is optimal as at the fingertip the PPG signal tends to be clear and not very noisy. Care needs to be taken however to ensure the sensor does not move when it is touching the fingertip. For initial data set acquisition and algorithm development, the fingertip implementation will be used for this reason until the wrist PPG sensor development is finished.

The same sensor has been tested acquiring real time data from the wrist mounted implementation. On the wrist the waveforms tend to be noisier and will require further filtering and signal processing to develop a signal of sufficient quality for use in real scenarios.

C. Prototype wrist mounted PPG data acquisition system

Based on the PPG measurement system described in the previous section, the WSN group at Tyndall have developed an application specific, new, PPG sensor system, which will enable data sets from the wrist to be taken directly and is of a form factor appropriate to that envisaged for the final product. A picture of the board is shown in Figure 4, where one can see the main components on a 5cm by 3cm sized PCB microsystem. The board contains a USB connection module, the microcontroller, the ECG sensor and the new PPG sensor circuit, which are described in the next few paragraphs. A 3D printed enclosure has been printed for the board, which makes it able to be used as a wrist mounted system and facilitate collection of data from participants in a reliable, repeatable and accurate fashion.

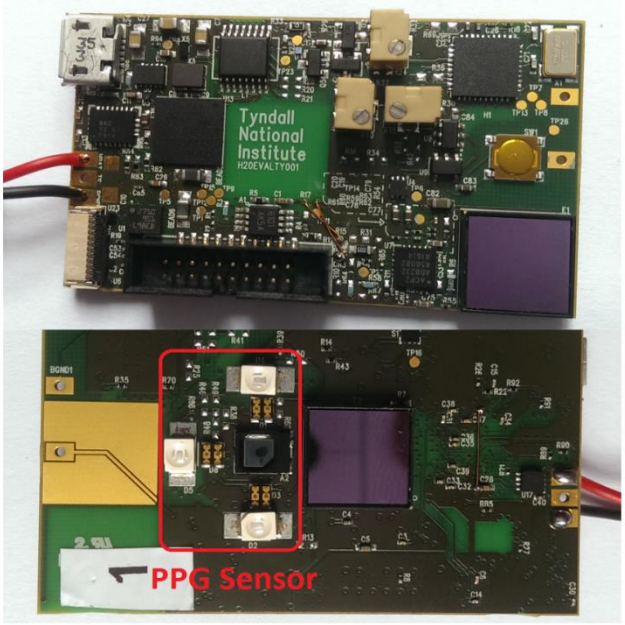

Figure 4. Wrist mounted PPG data acquisition system.

Experiments have shown that variation in the position of the LEDs, as well as the particular power and wavelengths of different LEDs impact significantly on the quality of the PPG signal obtained.

To evaluate different placement scenarios, we have designed an integrated circuit with nine LEDs mounted in a circular manner around a photo diode, three green LEDs, three red and three infrared are used for this experimental setup. Diodes are arranged around the photodiode, as shown in Figure 4. This series of experiments is currently underway and will enable the design team to find the optimal configuration of diodes from the perspective of position, colour (wavelength) and intensity.

The new PPG sensor circuit is designed with the intention to test different configurations, communication protocols and positions of LEDs and photodiode within the same board. There are three experimental setups implemented in the same board for this system to optimise PPG acquisition parameters. A block diagram of this circuit is shown in Figure 5, which describes the flow, how the MCU can control LEDs through the three LED controlling plans.

In option A (Plan A), an additional integrated circuit (IC) to MCU will control which LEDs will be on and the limit of current intensity. This IC has an analog output so that we can vary very precisely the intensity of the light output from the LEDs to achieve the optimum level for wrist monitoring of PPG signals.

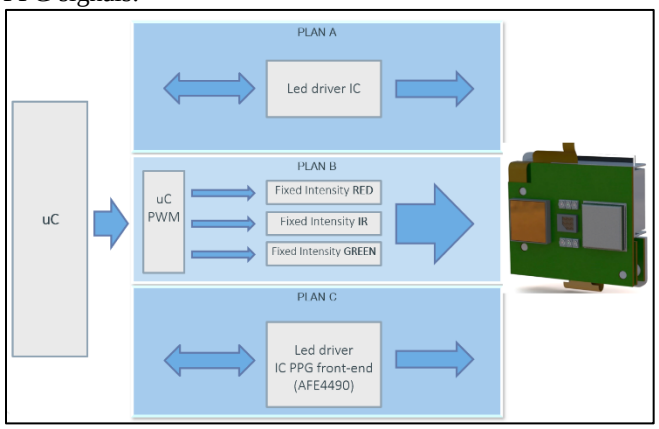

Figure 5. Three different test configurations of LEDs from PPG sensor.

In the option B (Plan B), every colour group (green, red and infrared) is connected to a potentiometer and Pulse Width Modulation (PWM) unit of the MCU. This will enable variation of the intensity of the LEDs very precisely. Also in this case, the output is analog and the ADC can be used to read data.

The option C (Plan C) requires the integration of an additional IC also. This chip (Analog Front End - Texas Instruments AFE4490 [17]) controls the state of LEDs in a similar way to option A, except that LEDs here can be controlled only in groups, so there is the same intensity for all the red LEDs for example. In this case, the output is digital, and eliminates the usage of the ADC.

D. Sensor Data Acquisition System evaluation

To calculate PTT, we use the peak of the ECG waveform and the peak of the PPG wave. Other features of waves can be used, like the beginning of QRS complex in ECG or the segment with the highest slope in PPG signal, but peaks are easier to detect and provide the fastest route to an initial prototype implementation for clinical tests. Additional tests in the future can carry on to determine if other features of the waves may give similar or improved accuracy. To identify the required peaks in the signals an initial sampling frequency of 100Hz was used. The sampling rate can be increased in future experiments if additional features need to be detected which will require higher precision [18]. The Maxim PPG sensor has a digital output using an SPI protocol and it generates an interrupt after each sample is taken. The USB virtual COM port is enabled in the microcontroller, so we use this interface to send data to and from a PC to develop the data analytics. The PPG and ECG data sets are sent in real time to the PC, and plotted to check the quality of the waves. As is described below in this section, the waveforms from the sensors when located on a fingertip are of superior quality and are what we are using for the initial algorithm development in the calculation of PTT.

We tested the same sensor on the wrist. It was quickly apparent that the sensor needs much more time for the data readings from the wrist to stabilize as compared with when it is worn on fingertip. Even after we start to see the standard shape of the wave, it is very noisy and hardly readable, and also we lose the waveform with small movements of the sensor or hand. In Figure 6, we can see the best wave we could get from the Maxim sensor when worn on the wrist. For the final wrist mounted system, additional software filtering and signal processing are required on the waveforms for this reason.

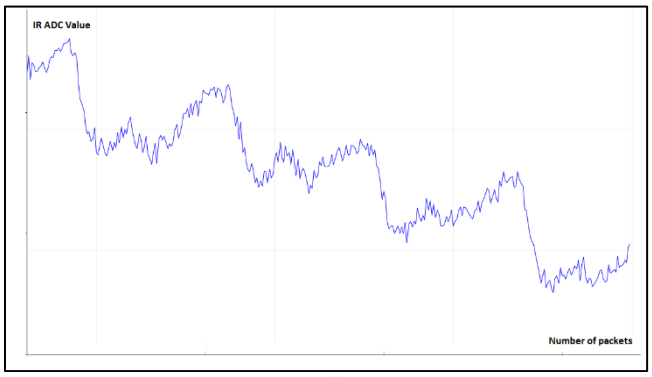

Figure 6. Real time PPG data from Maxim sensor on wrist.

The ECG sensor is combined with a circuit created using an Analog Devices (AD8232 [19]), which was designed to record ECG signals using classic electrodes, but is modified and used with EPIC ECG electrodes in our case. This chip has an analog output and is sampled at the same rate, 100Hz, as the PPG wave. The MCU's ADC unit is used, and the data from ADC registers are read every time an interrupt is triggered by the PPG sensor. The same sampling rate (of 100

Hz) for both waves is used in the literature [20], and we have also implemented this, which is sufficient to evaluate the system during this initial phase. It means that we will use only one interrupt service routine in the microcontroller, and less instructions will be executed to run the algorithms and measure time difference between peaks of two waves.

As seen in Figure 7, the red colour wave is the real time ECG signal from the sensors. The signal is of sufficient quality to be able to detect the peaks as this is the main feature we will extract from ECG at this stage. This signal is plotted from raw data, so no post processing has been implemented. In next revision of the software, software noise filtering can be applied on the signal, which would result with a clearer graph, higher accuracy and other features of the signal can be detected. In Figure 7 again, we can see the plotted waveforms and datasets needed to determine PTT. The blue, lower graph is the PPG waveform from the fingertip. This wave from fingertip is clear and consistent, which means peaks can be easily located. Both waves are shown on the same plotting area to visualize PTT. Time difference between two vertical segments is the value of PTT.

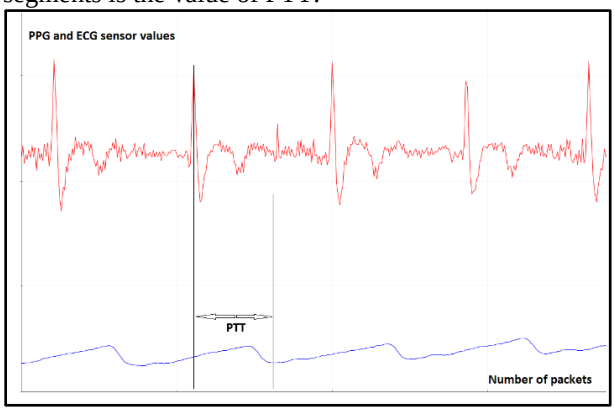

Figure 7. Real time ECG and PPG data on the same plot and PTT.

Figure 8 shows a close up representation of the ECG peaks QRS complex. The R peak is considered a starting point to measure PTT for the purposes of our algorithm development. The PPG wave is inverted, as the wave shows the level of absorption, so it means at the lowest peak the light is absorbed the most and this is because of the volume of the blood in vessels at that moment.

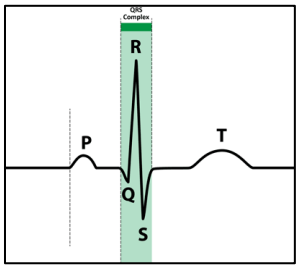

Figure 8. ECG QRS complex.

So, the distance between the two black vertical lines on Figure 7 is the value of PTT used in our evaluation and future calculations of blood pressure changes.

IV. Firmware and Calculation of PTT

In the previous section were shown results from the testing of the hardware and software of the initial evaluation system. With the exception of the PPG sensor, the design of the Tyndall system designed as a custom PCB board (H2O device) the same hardware components as described in Section III are used. The PPG sensor designed by the Tyndall team and described in Section III is used in the H2O device in place of the Maxim PPG sensor. Using the new PPG sensor designed we were able to record less noisy PPG signal waveforms from the wrist. The improvement in signal to noise ratio can be seen if the PPG signal shown in Figure 6 is compared with the PPG data shown in Figure 10, where the PPG signal as measured on the wrist by the Maxim sensor and the Tyndall sensor are shown respectively. The new PPG sensor is also used while performing clinical measurements on 33 participants as part of the system validation trials, and in all cases, there were no issues on reading sufficiently clear PPG signal. Results of calculation of PTT during clinical trials are shown in Section VI, Table I.

In the first version of the software, PPG and ECG are recorded at 1 kHz sampling rate compared to 100Hz in the previous version. A sampling rate of 100Hz has a 10ms time difference between two points, which lower the accuracy of the estimation to approximately ±2mmHg.

Sampling time is measured by timer counter interrupts. The counter interrupt is also used to measure the time between samples and to convert the number of samples to values of milliseconds. Windows of 4 seconds are used to collect the data, which afterwards are processed while the next window of data is collected. We have used windows of duration of 4 seconds two reasons. Firstly, in this time period it is generally possible to locate at least three heartbeats in one window, enabling the calculation of heart rate and PTT. Secondly, a longer window would delay the process of calculating PTT. When the user touches the ECG electrode, the sensor requires some time to start reading the ECG waveform. As averaging is used to localize the R complex, most of the time algorithms would be unable to calculate PTT. This mean that calculation will be performed in the next window. If the window is longer, overall execution would take more time to finish. Collecting samples and running the algorithms simultaneously means that in between sample readings, the processing power is used to execute parts of the algorithm with the data from the previous window. In parallel, after completion of one window, collected and processed data are transmitted through serial COM port. Transmitted data is formatted so as to conform to the communication protocol, designed to communicate to the interface, which is described in the following section.

To derive systolic and diastolic BP from PTT it is required to locate three points on ECG and PPG, therefore to determine systolic PTT (SPTT) and diastolic PTT (DPTT) [21, 22]. The time difference between the peak of QRS complex of ECG, labelled with ‘A’ in Figure 9, and the minima of PPG signal, labelled with ‘C’ is marked as SPTT.

And the difference between the peak of QRS complex and the maxima of the PPG signal, labelled with 'B' in Figure 9, is labelled as DPTT.

The peak of QRS is located by averaging the ECG signal three times and setting the value of averaging as a threshold. Points 'B' and 'C' are located by exploring PPG signal in a time distance range where PTT value usually is. The algorithm will start scanning for minima first. Once it establishes the minima, the algorithm will continue to search for the point of the inflexion on PPG signal, which should be between minima of PPG and ECG peak. Knowing that sampling frequency is 1 kHz, can also be concluded that the number of samples between two points is also the time distance in milliseconds.

Heart rate is also calculated from the time difference between the ECG peaks and is sent to the interface. After the calculation of PTT, a number of 12 values of SPTT and DPTT are collected in an array, averaged and processed to remove possible out of range PTT values.

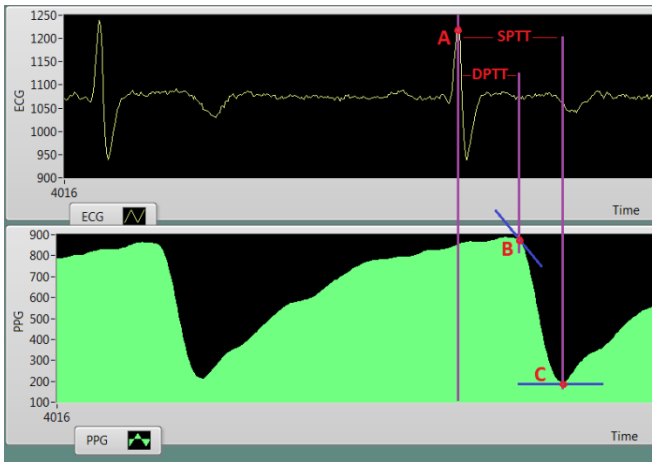

Figure 9. Selected points to calculate PTT values

V. Interface and Communication Protocol

As described in the previous section, in the final version of the wrist-worn sensor system all signal and data processing is to be executed by the microcontroller embedded on the device. The system hardware in use, the H2O device, does not have display included. Tools available were not useful in our case as showing at the same time single values and graphs with different scales is required. A custom Graphical User Interface (GUI) that can communicate with the board and visualize all needed data sent from the board is created.

While plotting, the interface should also be able to show the single values of PTT, heart rate, blood pressure, and before averaging raw PTT values. Another important feature needed was being able to export recorded data in a particular, easy to read format. Exported data are stored for potential data re-processing in the future.

The interface communicates with the board through a serial COM port. There are three plotting windows implemented on the interface, as shown in Figure 10. ECG and PPG are plotted at 250 Hz, ¼ of the frequency of sampling. The frequency of 250Hz is sufficient to plot the complete waveform and it is more efficient for the microcontroller. The window labelled with "PTT" plots last 25 values of systolic PTT (SPTT) and diastolic PTT (DPTT) before being averaged. On the right side of the PTT window, are printed the last 12 values of PTT, which are used to calculate the mode and derive the single value of PTT. Single values of PTT are printed in two textboxes, labelled "DPTT" and "SPTT".

The second functionality of the interface is the ability to personalise the datasets and export them to excel for further analysis and validation if necessary and to enable the development of the algorithms to establish the parameters affecting BP. Associated with the button labelled "Excel" is a textbox to write the name of the subject. After clicking with a mouse on it, a new window shows a questionnaire for the subject to capture all relevant data such as gender, age, arm span, dietary factors and physical activities. All the data can be exported into a custom excel format for analysis. In the excel file, will also be exported by default all the data from the plotting windows.

This interface was developed to enable the testing and evaluation of our BP monitoring system, but it can also be useful to be used in other applications requiring visualisation of serially transmitted sensor data. It is designed in such a way that if you follow the simple communication protocol, it will plot data from applications that require a similar functionality.

In order to be able to use this interface for other purposes, the communication protocol is described briefly. The general idea of the protocol was to be generic, so it would be easily expanded if required. To do this, for every plot or textboxes values, a specific character is assigned. Data is sent in one single array with all the characters preceding the values. This means that if one needs to plot graphs and print single values simultaneously, using the same COM port, then this interface can be used.

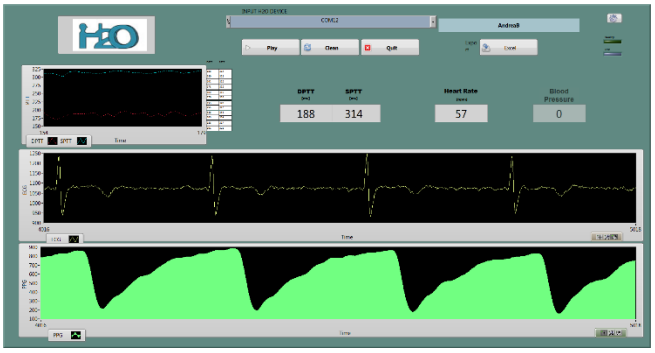

Figure 10. A view of the main window of the interface

Figure 11 illustrates the protocol and the creation of the array that would be accepted by the interface. The order of values per window is not important as the parser in the interface processes separately every string between two commas.

Generic format:

ECG1,	ECG2,	ECGn,	PPG1,	PPG2	PPGn,	PTT1,

…	PTT2	PTTn,	DPTT,	SPTT,	HR,	BP,

Example: 4Hz

E25,	E27,	E20,	E31,	P74,	P86,	P55,	P69,

…	T340,	T344,	T341,	T335,	D212,	S341,	H65,

Figure 11. Generic format and an example of the communication protocol

The string parser starts by reading the array. Once it recognizes the START character, it will look for the value, which should be immediately after the character, and a comma is the end of one value. The recognized value is printed on the respective plot. If the character corresponds to one of the textboxes, the value is shown in a textbox. In case of plots, you expect to have more than one value. In our case, 1000 values every 4 seconds are sent and plotted. The reasons for this size of windows as explained in Section IV are: not delaying the overall execution time in case the algorithm fails to calculate PTT in one window, and generally a 4 second window is sufficient to locate three heart beats. Then, array members are parsed in sequence, printed, and shifted to the left.

If this interface needs to be reused for other purposes, all one has to do is to send a sequence of the values with the corresponding values for each window. An example is given in Figure 11. In this example, 4 samples per second are sent, therefore plotted. The last 3 values in the array, are textbox values, and they are shown in textboxes until the new value arrives.

VI. CLINICAL TRIALS PROTOCOL

Studies mentioned in the Section II show clearly that PTT and BP are related, but different factors, also discussed in Section II, with time are causing changes in this relationship [21]. In order to explore better those factors, the influence they have in BB-PTT relation, and potentially including those findings in BP estimation algorithm, a clinical trial protocol is designed and measurements are carried-on with volunteers. In this section are shown details from the protocol and processed results after measurements.

Before starting with measurements, based on literature, a number of different factors that may affect BP-PTT relation are listed. Based on that, the study is divided into the interventional part and non-interventional one. An interventional study is a type of clinical study in which participants are assigned to groups that receive one or more intervention/treatment so that researchers can evaluate the effects of the interventions on biomedical or health-related outcomes. The assignments are determined by the study's protocol. Participants may receive diagnostic, therapeutic, or other types of interventions. In this study, is has been started with the non-interventional part, which can be completed faster and can provide feedback for the interventional part, if it is needed.

Clinical trials protocol is designed in collaboration with cardiologists, and this research study has received Ethics approval from the Clinical Research Ethics Committee (CREC) of the Cork Teaching Hospitals. The study is also covered by the insurance policies of the University College Cork. The interventional part should go through the same procedure, once it is considered necessary to be carried-on. The process of clinical trials and how data will be applied is described in a flowchart in Figure 12.

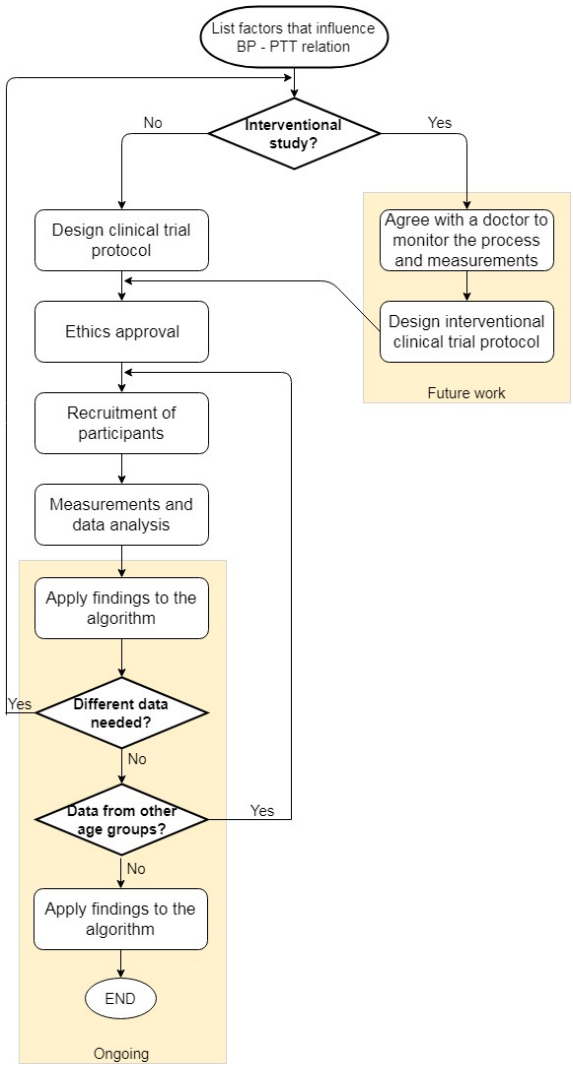

Figure 12. The flowchart of the process of data collection and data usage

During the first phase, 33 participants were recruited. Participants are all between 20 and 35 years old. They were suggested to log all their activities and food they intake from 6 pm of the day prior to the day of measurements and until

the last measurement. There are five measurements during one day, and they are organized as follows:

1. In the morning, within 2 hours after waking up
2. Within 30 minutes before lunch
3. Within 1 hour after lunch
4. After 4 pm, before coffee (if participants use coffee)
5. 30 minutes after coffee

The protocol is designed in such a way, that at the conclusion of the experiment we can have datasets which allow us to explore the relationship between BP-PTT as measured in the morning, compared to an evening measurement. In addition we can explore the relationship between these parameters before and after drinking coffee, as well as before and after eating lunch. In this way we can, or see any potential influence of a particular food or different activities on the BP-PTT relationship. After designing the blood pressure estimation algorithm and evaluating the accuracy and results, measurements with other age groups may be useful to undertake if the data from the first trials are useful for the estimation algorithm.

Each measurement took approximately 10 minutes to carry out. The measurements were carried out while participants were in a seated position. The standardised position of the patient during the experimental measurement session is shown in Figure 13.

Figure 13. Set-up of the measurements during clinical trials

As a gold standard, a medically approved BP monitor, BP-801 from Withings, is used to measure blood pressure at the same time as the H2O system developed by the team. This product has received clearance from the Food and Drug Administration (FDA) in the USA and is compliant with European medical device regulations [23]. During the experiment, PPG is recorded continuously using the H2O device. In order to see and record ECG, the user needs to place the index finger of the opposite arm on the electrode to read the differential signal. A closer view of how the watch is worn and the position of the finger is given in Figure 14.

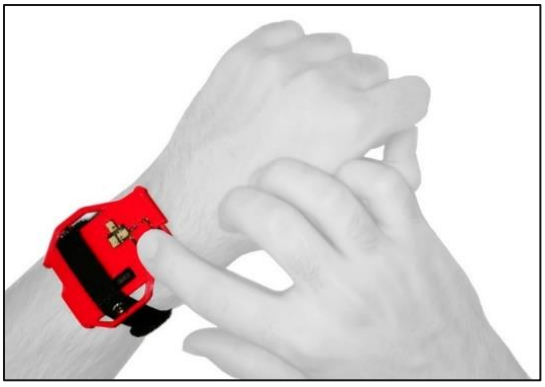

Figure 14. Board with enclosure and worn on the wrist

The procedure is as follows:

1. Sit down, with feet flat on the ground and the back supported
2. Wear the gold standard commercially available BP monitor and take a BP measurement (left arm)
3. Wear the H2O device on the opposite arm with where commercial BP monitor is worn (wrist of right arm)
4. 3-5 minutes after the first BP reading, take the second BP reading using the BP monitor
5. Touch the ECG electrode of the H2O device with the index finger of the opposite arm to close the electrical circuit as described above.
6. Record the ECG signal and calculate PTT for no more than 2 minutes

Before taking the measurement in the morning, for each patient, we also measured arm span, height, the weight of the participant, as well as the room temperature at the time of measurement. To ensure the most accurate results, and to make the participants feel more comfortable and relaxed with the air pressure cuff, two measurements are carried-on within one session.

In general it was observed that the blood pressure dropped in the second measurement, after sitting still for 3-5 minutes. As a result, based on our measurements and suggestions from doctors, the second measurement is the one chosen to be the more accurate result, and was registered as a BP value for one session. In some cases, first and second measurement were significantly different from each other, and a third measurement need to be taken and recorded.

Processed results of measurements are presented in Table I. Three records of diastolic BP-PTT relation are discarded because the algorithm was unable to determine the value of DPTT as the PPG signal was not clear. First column of Table I shows four categories of morning and evening differences of BP and PTT. The second and the last column show the number of subjects in each category for systolic BP and diastolic BP respectively.

Table I. Morning and Evening relation of BP-PTT

Differences between morning and evening in BP and PTT	Number of subjects [Systolic]	Number of subjects [Diastolic]
Increased BP – Increased PTT	2	6
Increased BP – Decreased PTT	14	3
Decreased BP – Increased PTT	6	10
Decreased BP – Decreased PTT	11	11
Total	33	30

VII. PHASE 2 DESIGN STRATEGY OF THE DEVICE

Currently, a second generation system is under development incorporating all the necessary system functionalities to enable physiological monitoring. Designed around a "Flex/Rigid" system design methodology so as to enable a highly miniaturised robust prototype, the system functionalities include sensors for ECG (Electrocardiography), SpO2 (Oxygen Saturation) levels, Heart rate, Blood pressure and Activity/Motion tracking. Communications modalities include Ultra Wide Band (UWB) for both communications and location tracking/ranging as well as Bluetooth Low Energy (BTLE) to facilitate communications between the smartwatch and any mobile device belonging to the user for additional data analytics and visualisation.

Figure 15. Details of the Phase 2 design of the device

In Figure 15 is shown how the physiological sensors are placed in the new device design. There is a difference in the design of the PPG sensor in this version compared to the PCB used in the first phase of experiments described above. Two photodiodes are used instead of only one as in the previous version and also the SpO2 sensor is designed separately in which a dedicated circuit, photodiode, red LED and infrared LED are used. The complete device design is presented in Figure 16.

Figure 16. Design of the final device (future work)

VIII. CONCLUSIONS AND FUTURE WORK

There is no doubt that a BP monitor that would be accurate, reliable, cuffless, and comfortable with easy to carry out frequent or even continuous measurements would be priceless for clinical diagnosis of cardiovascular illness diagnosis. For decades, research has been carried out to achieve this goal. Pulse transit time (PTT) seems to be the most promising method to achieve it, based on literature. But until now, one of the challenges to be addressed is in the development of an appropriate data acquisition system to provide the necessary data sets for such a system. The main challenges are: vessel's properties changing from person to person, vessel's properties can be changed by factors within body or ambient conditions and clear data acquisition from comfortable wearable sensors.

The WSN group at Tyndall is currently developing such a system. In this paper, we are showing practical results of the first phase of the work in progress. The main focus of this stage is to deliver a complete system that allows proceeding with a deeper evaluation of the BP-PTT relation. The first part of the study is focused on the evaluation of the computing hardware, sensors, custom board design and data acquisition. Initial results of evaluating the integrated ECG sensor and PPG sensor are shown during the first three sections, including the new PPG sensor design for the wrist.

In Sections IV and V are presented results on developing the required algorithms and software to calculate PTT from biosignals and data visualisation.

Finally, we have used the new PPG sensor designed, the Tyndall custom PCB board and developed algorithms to run measurements with participants in clinical validation trials with clinical partners and continue the development of the required processing and algorithms to provide BP measurements from PTT measurements. A list of factors that affects blood pressure significantly has been created, and measurements are carried out to try to quantify the influence they have. These measurements could enable the development of the required algorithms that would relate BP and PTT, which is the main part of the complete study to be reported in subsequent publications.

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