Non-Invasive Method of Blood Pressure Measurement Validated in a Mathematical Model

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Abstract- The non-invasive method of measuring systolic and diastolic pressures with the use of an automated occluding cuff which results in valid estimates of mean pressure, but questionable estimates of systolic and diastolic pressure due to inappropriate algorithms and proper hardware. It is also sensitive to differences in pulse pressure and artery stiffness. To improve the accuracy of systolic and diastolic pressure using cuff pressure oscillation remains an open challenge. It can be made more deterministic by using LED’s of proper wavelength considering the absorption of light by the blood, photodiodes, considering the elasticity of the cuff and its inflation and deflation parameters along with the selection of proper pressure sensor. The method involved to execute these is oscillometric method which is a more advanced method for blood pressure monitoring. This model reproduces the realistic cuff pressure oscillations. The systolic and diastolic pressures are then extracted using regression analysis in face of varying pulse pressure and arterial stiffness. Proper hardware and accurate input yields in précised and deterministic results.

Keywords- Oscillometric, non-invasive, arterial stiffness, pulse pressure, automated cuff, regression analysis.

I. INTRODUCTION

Blood Pressure (BP), sometimes referred to as arterial blood pressure which is one of the principal vital signs is the pressure exerted by circulating blood upon the walls of blood vessels. The rate of mean blood flow is dependent on both, the BP and resistance to flow provided by the walls of blood vessels. BP is usually expressed in terms of systolic pressure (SP) over diastolic pressure (DP) and is measured in millimetres of mercury (Hg). The normal BP of an adult is 120/80 mm of Hg. This is 120mm of Hg over the atmospheric pressure of 760 mm of Hg. So, the overall pressure is 880 mm of Hg.

The Mean Arterial Pressure (MAP) is the average over a cardiac cycle and is determined by the cardiac output (CO), system vascular resistance (SVR), and central venous pressure (CVP). Pulse Pressure up-down fluctuations of the arterial pressure results in a pulsatile nature of CO. It can be simply calculated from the difference of the measure of SP and DP.

Non-invasive Blood Pressure measurements (NBP) are quick and easier to execute and also cause minimum stress to the patient. This technique uses an automated cuff and a pressure sensor to detect the pressure signal when the cuff is deflated. The pressure at which the first pressure signal is received is recorded as the SP and similarly DP is recorded with the last pressure signal.

As with all the practical research devices, this device also has merits and some challenges which need to be faced and accordingly revamped, such as, (1) high motion tolerance of NBP devices, (2) the pressure in the cuff must be steadily scrutinized so as to avoid any mishap, (3) the devices need a yearly calibration for deterministic results, (4) some errors that are accounted which must be keenly guarded are, (i) the rapid deflation of the cuff, (ii) cuff’s elasticity to restrain the rated pressure.
In this paper, a mathematical model for NBP measurement is presented which could capture the systolic and diastolic pressure as well as varying pulse pressure along with artery stiffness. Pressure sensors are designed for proper operations and the output response is compared with the known medical devices to verify SP and DP obtained through this device and measuring the accuracy and precision achieved.

II. OSCILLOMETRIC METHOD
The oscillometric method of BP measurement takes into account the intra-arterial pulses to the occluding cuff which surrounds the limb or artery (finger in this case). The measurement is done by placing the cuff upon the artery and inflating it till the blood flow in the artery stops. The pressure in the cuff is then released slowly in steps of 4-8mm of Hg using a pressure release valve. The blood starts flowing and its flow changes from turbulent to laminar creating a korotkoff sound, which is then measured by a pressure sensor. The data is then recorded using data acquisition system and resulting oscillogram is detected and processed at each pressure step.

![Oscillogram obtained by releasing the cuff pressure](image)

Fig.1. Oscillogram obtained by releasing the cuff pressure

The pulsations or the korotkoff sound starts at the systolic pressure and ends at diastolic pressure while releasing the pressure from the cuff.

Due to difficulties in measuring the SBP because of oscillating amplitudes, a filter of order 3, with a cut-off frequency of 50 Hz along with curve fitting of second order is used to filter the signal and noise and enabling the ripples in the passband and stopband thereby reducing the loss of signal power and data.

III. MATHEMATICAL MODELLING
A. Non-Invasive Blood Pressure Measurement model
NIBP mathematical model involves inflation and deflation of the cuff by the use of motor for a précised time upto a pressure of 300 mm of Hg and this pressure needed to be controlled using a pressure switch which will cut-off the circuitry of the motor as soon as the pressure is reached to its set-point which in this case is 300 mm of Hg. As soon as the cuff starts deflating, blood start flowing in the arteries which in turn results in a turbulent flow also causing a kortokoff sound which is detected by the pressure sensor, and the pressure sensor gives the systolic pressure reading. Similarly, when the blood starts flowing freely with the full diameter of the artery, then its flow changes to laminar flow and that kortokoff sound stops, that reading is then sensed by the pressure
sensor is recorded as diastolic pressure. The mean arterial pressure (MAP) is then calculated which is the average over a cardiac cycle and is determined by cardiac output (CO), system vascular resistance and central venous pressure (CVP).

\[ MAP = (CO - SVR) + CVP \]  
\[ MAP \approx P_{dias} + \frac{2}{3} (P_{sys} - P_{dias}) \]  
\[ P_{pulse} = P_{sys} - P_{dias} \]

The pulse pressure is then calculated from the difference of measure of systolic and diastolic pressure.

B. Signal Conditioning of Input Signal

The input signal obtained is a voltage signal which is converted to the pressure signal with the use of equations specified in the specification sheet of the sensor which is used to sense the input data. The signal obtained as the pressure signal is weak and noisy.

An Infine Impulse Response (IIR) filtering technique is used to eliminate the noise. The filter is a combination of analog filter, its prototype and the digital filter. The filter we are using is the Inverse Chebyshev filter. The main feature of this approximation is the ripple in the stop-band. The pass-loss in this type of filter is a monotonic function of frequency, as in the case of Butterworth filters.

![Fig.2. Magnitude response of inverse chebyshev filter](image)

IV. GRAPHS & CIRCUIT

The scaling frequency of inverse chebyshev filter is defined equal to stop-band edge frequency. The response of Inverse Chebyshev filter is given as

\[ |H(j.\omega)| = \frac{e^{2\theta N}}{1 + e^{2\theta N}} \]  

A. Mean Arterial Pressure

The MAP and Pulse pressure calculated from systolic and diastolic pressures is shown below in Fig. 3, the graph gives a clear overview and explanation of the above equations no. (2) and (3).

![Fig. 3. Mean Arterial Pressure](image)
B. Motor Driving Circuit

An air pumping motor is used for inflating the cuff and creating the required pressure which is to be sensed by the pressure sensor or a LED- Photodiode coupler.

This circuit is used for efficient working of the motor keeping in mind the current rating. It uses two MOSFET’s that are n channel and p channel along with IRF510 and diode IN4007 which resists the motor to operate in one direction only.

C. Device Circuitry

It is a combination of NI myRio, which is a microprocessor based system along with FPGA i.e. field programmable gate array, thereby, making the complete device standalone and provides high determinism. The device is then connected to various digital and analog inputs or outputs such as the motor, a circuitry of infrared led and photodiode along with the pressure valve and a LCD display. The input as shown in Fig. 3, is provided by the device to the motor for its operation. It is a pulse width modulation signal commonly known as PWM signal for a period of time required to inflate the cuff to a pressure of 300 mm of Hg.

![Fig. 4. Sample PWM Signal](image)

As shown in Fig. 2, the device is programmed using the graphical programming using NI LabVIEW, and the program is then dumped into NI myRio’s memory.

![Fig. 5. Sample LabVIEW Block diagram Window](image)

The wavelength of LED is selected on the basis of the diameter of the red blood cell which is 7-8 microns and size of the artery which is 2mm in diameter. The wavelength absorbed by the red blood cells lies in the IR region and the suitable photodiode is selected to generate the output voltage which is then calibrated using proper specification sheet and the algorithm. The pressure valve used deflates the cuff and allows the blood to flow again which creates a pressure signal that is received by the photodiode and the value so obtained is compared to the data sheet and the diastolic and systolic pressures are obtained.

The wavelength so chosen is then changed according to resolution to obtain more accurate readings and reducing the scanning time and moving towards beat to beat pressure measurement. Proper filters are used with their cut-off frequencies along with the feedback so as to minimize the errors and curve fitting of second order is carried out for the proper plotting of the waveform generated through the photodiode.
To obtain the value of systolic and diastolic pressure, the waveform is compared by overlapping the waveform over an ECG waveform or a blood pressure waveform obtained from any other device using pressure sensor to calculate the peak heights which in turn will determine the value of SBP and DBP. The values are stored and recorded to calculate a mean error which is obtained as the difference in readings of syphygmo-feno manometer and the normal blood pressure meter.

![In-beam Prototype](image)

**Fig.6. In-beam Prototype**

V. CONSEQUENCES
There is an alarming need of highly accurate and precise Blood Pressure monitors to substantiate the monitoring done through mercury whose accuracy is also not good and it also cannot be used by an average person. The BP monitor market is growing rapidly due to increasing number of hypotensive and hypertensive patients, who require time to time BP monitoring. WHO has confirmed that approximately 12.8% of total deaths in a year occur due to BP problems and its improper or careless monitoring.

There is an alarming need of a product through which we can monitor the blood pressure with high accuracy and high precision which is commonly called as deterministic property of the product, along with it, this product also provides high comfort level to the patients because the inflation and deflation of the cuff on the arm sometimes causes irritation, so shifting the cuff from arm to second phalynx will be a huge improvement along with improved scanning time and its portable nature.

Therefore, this device will provide a great market, finding its efficient use in ICU’s, CCU’s along with the high determinism, high comfort level, alarms, emergency stop buttons which will make the device very much handy and will not ask for too much knowledge for its operation. The LCD used in the device makes the device even more user friendly providing a great user interface.

As with all the practical research devices, this device also has merits and some challenges which need to be faced and accordingly revamped, such as, (1) high motion tolerance of NBP devices, (2) the pressure in the cuff must be steadily scrutinized so as to avoid any mishap, (3) the devices need a yearly calibration for deterministic results, (4) some errors that are accounted which must be keenly guarded are, (i) the rapid deflation of the cuff, (ii) cuff’s elasticity to restrain the rated pressure.

VI. CONCLUSION
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