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Development of Blood Pressure Measurement Device Using The Curve Fitting Method

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Abstract: In present study, an automatic blood pressure measurement device was developed to perform measurement on the arm. The developed blood pressure measurement device was also used as display and control device. On this device, the curve fitting method, which is a very common numerical analysis method, was used to predict blood pressure. Resistor-Capacitor (RC) and digital filters were preferred to process and filter signal. Various tests were conducted on 21 individuals under the supervision of specialist. The obtained results showed that a prediction accuracy of 94.67%, 92.51% and 97.68% could be achieved for systolic and diastolic blood pressure and heart rate values, respectively.

Keywords: *Blood Pressure, Curve Fitting Method, Digital Filter, Polynomial, Signal Processing*

1. Introduction

Hypertension is an important social health problem which causes permanent disability and death worldwide. On the other hand, it is in the first place among the "causes of preventable death" [1]. An important part of hypertensive patients is not aware of their high blood pressure. This situation further increases the importance of hypertension. The negative effects of high blood pressure occur suddenly, and these effects involve various risks that can result in death. This shows that blood pressure should be measured as accurately as possible, and that patient motivation should be kept as high as possible. In studies published recently, the importance of blood pressure measurements at home has been particularly emphasized, in terms of anticipating the development of hypertension-related organ damages [2], [3]. Because of the white coat effect, measurements performed in a hospital environment are not healthy enough. Therefore, no reliable data can be obtained about patients' daily blood pressure values. In addition, it has been reported that home-based automatic blood pressure measurement devices motivate individuals against hypertension treatment and increase their rates of continuing treatment [3].

Various blood pressure measurement devices have recently been proposed in several studies [4]-[7]. In the first of these studies, a reporting system was developed for hospitalized patients [4]. In this system, patients' blood pressure and body temperature are measured continuously, and these values are sent to their doctors via a wireless connection. Blood pressure and body temperature measurements performed on five individuals were compared with the measurements performed with OMRON blood pressure measurement device and clinical thermometer. The results showed that the mean errors in measurements were ±4 mmHg for blood pressure and ±0.17°C for body temperature. For systolic blood pressure (SBP) and diastolic blood pressure (DBP) estimation, respectively, 0.55 and 0.85 fixed ratios between the oscillation amplitudes were used. In the second study, a wireless blood pressure measurement device was developed where Android-based smartphones were used as a display device [5]. Measurements performed on 12 individuals with the system using an analog filter were compared with the measurements performed with OMRON HEM-7111 and a mercury sphygmomanometer. The comparison between the results for SBP and DBP indicated that the prototype of the device achieved an accuracy of 98.63% and 97.13%, respectively, compared to those obtained with OMRON HEM-7111, and 98.99% and 98%, respectively, compared to those obtained with a mercury sphygmomanometer. SBP and DBP values were determined as points on the oscillation signals of previously determined threshold levels. In another study, a mobile phone with the iOS operating system was used as a display device, and a wireless blood pressure measurement device was developed [6]. The developed device was tested both through a Cufflink simulator and in a clinical setting. In the clinical tests performed on 19 individuals, a mean difference of 2.66 ± 2.71 mmHg for SBP and 3.42 ± 4.42 mmHg for DBP were obtained based on the auscultation method. The DC signal value at the peak point (Pmax) corresponding to the highest amplitude in the AC signal was determined as the mean blood pressure (MBP) value. For AC signals, fixed ratios of 0.42 and 0.77 were used to detect peaks corresponding to SBP and DBP values in the DC signal. In the latest study, a PC-based blood pressure measurement system, e-BPMS, was proposed for e-health applications [7]. The e-BPMS used by the PC as the indicator and the control device were compared with the measurements performed on 10 individuals and the OMRON blood pressure measurement device. The results showed that the mean percentage difference for SBP and DBP was ±0.95% and ±1.32%, respectively. Blood pressure was estimated using an oscillometric method through the interface developed using the Visual Basic 6.0 programming language.

In addition to the above studies, a wireless blood pressure measurement device was developed by İlhan et al [8]. Three different algorithms were used for blood pressure estimation and various tests were performed on 38 individuals. A prediction accuracy of 94.53% and 92.04% was obtained for SBP and DBP, respectively. A prediction accuracy of 95.14% was observed for

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heart rate. In another study, a wireless blood pressure holter was developed by İlhan [9]. The simple hill climbing algorithm was used for blood pressure estimation. Various tests were performed on 30 individuals in different age groups with this holter device. Test results showed that a prediction accuracy of 93.89% and 91.95% was achieved for SBP and DBP, respectively. A prediction accuracy of 97.66% was observed for the heart rate. In both studies, mobile devices were used as display and control devices. The blood pressure measurement device was placed on the cuff. Resistor-Capacitor (RC) and digital filters were used instead of analog filters on both devices.

This study was carried out to show that curve fitting method, a very common numerical analysis method, can be used to estimate blood pressure, but not to develop a commercial product or obtain approval. Therefore, an automatic blood pressure measurement device was developed to perform measurement from the arm. The developed blood pressure measurement device was also used as display and control device. RC and digital filters were applied to process and filter the pressure signals. Various tests were conducted on 21 individuals under the supervision of a specialist. Considering the results in the above-mentioned studies, the results obtained show that the prediction accuracy of the proposed device is at an acceptable level.

2. Blood Pressure and Heart Rate

Blood pressure is the pressure of blood on the artery walls. The pressure measured during the contraction of heart is expressed as the SBP, while the pressure measured during the relaxation of heart is expressed as the DBP. For SBP and DBP, 120 mmHg and 80 mmHg are considered as normal values, respectively [10]. When blood is pumped into large arteries, the fluctuations occur in arteries at the end points. These fluctuations, which express the heartbeats, are called heart rate. Values of 60 to 100 bpm for adults, 100 to 120 bpm for children, and 100 to 140 bpm for infants are considered as normal values [11].

Two different methods, invasive and non-invasive, are used to measure blood pressure. Invasive methods are generally preferred in hospitals and intensive care units; they involve placement of a catheter in the appropriate artery. Non-invasive methods do not require skin penetration. Instead, they measure the blood pressure by blocking the blood flowing through the arm by means of a cuff filled with air. The most common methods among these non-invasive methods are the listening and oscillometric methods [12]. Nowadays, automatic blood pressure devices usually perform measurement with the oscillometric method [13]. In this method, the cuff wrapped around the arm of the patient is inflated until the arterial blood flow is stopped. When the air in the cuff is gradually drained, the blood in the artery begins to flow again. This point is the moment when the Korotkoff sounds are first heard and small oscillations are observed at the cuff pressure due to heartbeats [9]. In the first stage, the amplitude of the oscillations increases when the air in the cuff is discharged. After a certain point, these oscillations diminish and disappear. This point is the moment when the Korotkoff sounds begin to disappear. The SBP corresponds to the cuff pressure at the point where the Korotkoff sounds are first heard and the DBP corresponds to the cuff pressure at the point where the Korotkoff sounds begin to disappear [9]. The cuff pressure where the oscillations with the highest amplitude during the air release from the cuff is expressed as the MBP [14]. When performing measurement using automatic blood pressure measuring devices, the MBP value is first determined. Then, using this value, SBP and DBP values are estimated using different algorithms, mathematical formulas, and constants. Because these methods are used for marketing products and remain commercially protected, there is no clear information [15]. Fig. 1 shows the relationship between cuff pressure, Korotkoff sounds, and oscillations observed in the cuff pressure.

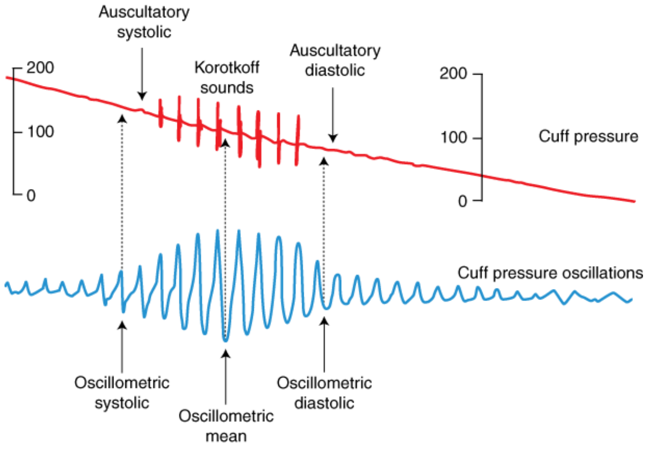


Fig. 1. Cuff pressure, Korotkoff sounds and observed oscillations

3. Method

3.1. Temporary Circuit and Interface

A temporary circuit was built to test the signal processing and filtering process and implement the proposed algorithm; a temporary interface was developed using the Microsoft Visual C# programming language. The STM32F407 Discovery Kit was used for the temporary circuit, while the other elements (pressure sensor, mini compressor, directional control valve, L293D motor driver chip, RC filter) was placed on a breadboard (Fig. 2). The data exchange between the STM32F407 Discovery Kit and the computer was provided via a USB connection. An interface was created using the Microsoft Visual C# programming language for monitoring the processing of signals from the pressure sensor, digital filtering, blood pressure, and heart rate estimation (Fig. 3). Establishing a connection using the STM32F407 Discovery Kit via USB, initiating and ending the blood pressure and heart rate measurements, calibration of pressure sensor, determination of signal reading intervals, monitoring the signals, processing and application of digital filter, calculation of blood pressure (SBP, DBP and MBP) and heart rate values were carried out through this interface. Thus, before the prototype was developed, the signal processing and filtering process to be used was tested and the proposed algorithm was applied. The STM32F407 Discovery Kit was used only to control the mini-compressor and valve, and to read data from the pressure sensor. After the appropriate digital filter and algorithm had been specified using the temporary interface, conversion into the code to be placed in the microcontroller was easily carried out.

In this study, both the hardware low pass filtering and the software low-pass filtering were used together to clean the noise in the signal received from the pressure sensor. A simple RC filter consisting of 750 Ω resistance and 0.33 μF capacitor was preferred for hardware filtering [16]. This filter has a cut-off frequency of 650 Hz. Four samples averaging was applied for software filtering. The performed experiments showed 650 Hz RC filtering and four sample averaging process reduce the noise level of the signal

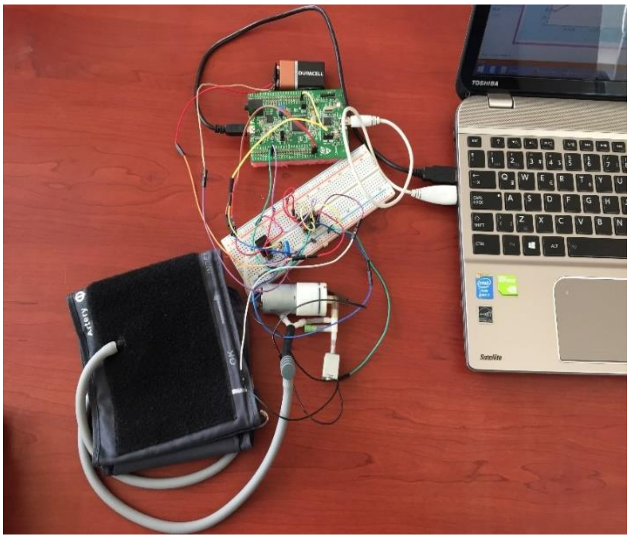


Fig. 2. Temporary circuit with STM32F407 Discovery Kit

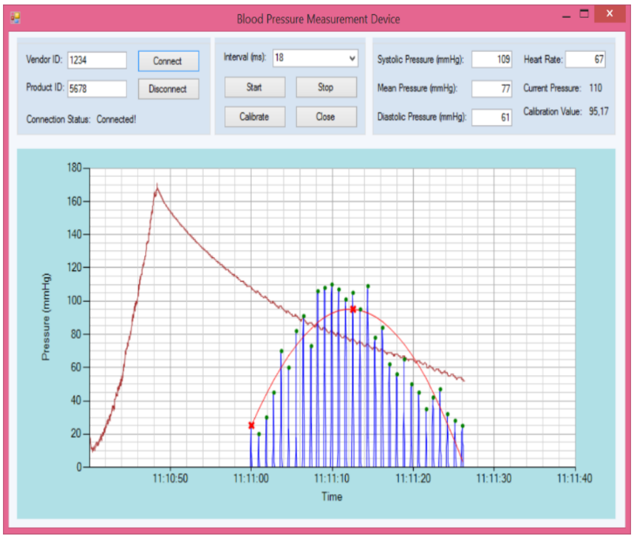


Fig. 3. Temporary interface created with Microsoft Visual C#

received from the pressure sensor from peak to peak to about 1 mV. As a result of this filtering, Mean Square Error (MSE) and Peak to Signal Noise Ratio (PSNR) values were calculated as 1.16104 and 65.79591, respectively. The signal, shown in brown, in Fig. 3 represents the cuff pressure reduced noise level. The signal, shown in blue, indicates the result obtained after the high pass filter (HPF) is applied to the cuff pressure signal. The HPF was applied to make the pulse peak amplitude more visible and detectable. In this study, as proposed in [8], a digital HPF with a cut-off frequency of 4 Hz was used.

In the oscillometric method, the pulse peak amplitudes should increase regularly between SBP and MBP and decrease regularly after the MBP. However, as can be seen from Fig. 3, after the high pass filtering applied to the cuff pressure, the resulting pulse peaks proceed wavily. That causes the largest amplitude pulse peak to be detected incorrectly, which is why the MBP value is incorrectly calculated. As emphasized earlier, automatic blood pressure measurement devices measure SBP and DBP values using various constants, mathematical formulas, or algorithms. Accordingly, they use the MBP value. A small error in the calculation of this value is also reflected in the SBP and DBP values, so the error rate of the blood pressure measurement device is higher. This study focused on this problem in particular, and the curve fitting algorithm, which is detailed in the next section, was used in the process to find the MBP value.

3.2. The Curve Fitting Method

There are two different approaches to a curve fitting procedure that depend on data errors: Regression and interpolation analysis [17]. Regression analysis is used to show the general tendency of error rates by a single curve, without having to pass on large values at each data point. Interpolation analysis is a representation of the error rate by a fitting curve or curve such that the small values pass through each of the well-known separate points. One of the methods used most often when performing regression analysis is the least squares method, which aims to find the coefficients that will minimize the sum of the squares of the error [18]. In the least squares' method;

When $y_{about} = a_2x^2 + a_1x + a_0$, (1)

$\epsilon = y_{real} - y_{about} = y_{real} - (a_2x^2 + a_1x + a_0)$ (2)

describes the error value.

$$S = \sum_{i=1}^{n} \epsilon_i^2 \quad (3)$$

n being the number of samples, the least squares method is used to find the coefficients a_2, a_1, and a_0 that will give the minimum sum of the squares of the error (S). The derivatives of these values are equalled to zero and the following equations are obtained:

$$(n)\, a_0 + (\sum x_i)\, a_1 + (\sum x_i^2)\, a_2 = \sum y_i \quad (4)$$

$$(\sum x_i)\, a_0 + (\sum x_i^2)\, a_1 + (\sum x_i^3)\, a_2 = \sum x_i y_i \quad (5)$$

$$(\sum x_i^2)\, a_0 + (\sum x_i^3)\, a_1 + (\sum x_i^4)\, a_2 = \sum x_i^2 y_i \quad (6)$$

The experimental values of x_i and y_i, belong to the problem being studied, are replaced in equations (4), (5) and (6) and three equations of three unknowns are obtained. When these equations are solved, coefficients a_0, a_1 and a_2 are found for the second-order polynomial. These coefficients are written in (1) and y_{about} equation from the second degree, corresponding to the given experimental values, are obtained.

3.3. Proposed Algorithm

When performing blood pressure measurement with the developed prototype, the cuff is first inflated. When the cuff pressure reaches 180 mmHg, the inflation process is stopped. Then, the air in the cuff is slowly deflated. Deflation process is done in such a way that 3 mmHg/second. When the cuff pressure drops to 50 mmHg, the deflation process is stopped. Finally, the air is completely deflated. This status is seen on the sample measurement given in Fig. 4. In this figure, the brown signals represent the cuff pressure and the blue signals represent the pulse peaks.

While the air is slowly drained, the order of the pulse peaks obtained at the HPF output are recorded as x_i values, and the amplitudes (peak values) of the pulse peaks are recorded as y_i values. x_i and y_i values of the sample measurement given in Fig. 4 are listed in Table 1.

Where n is the number of pulse peaks. The values listed in Table 1 are placed in equations (4), (5) and (6) and the following three equations are obtained.

$30a_0 + 465a_1 + 9455a_2 = 1986$

$465a_0 + 9455a_1 + 216225a_2 = 29095$

$9455a_0 + 216225a_1 + 5273999a_2 = 522181$

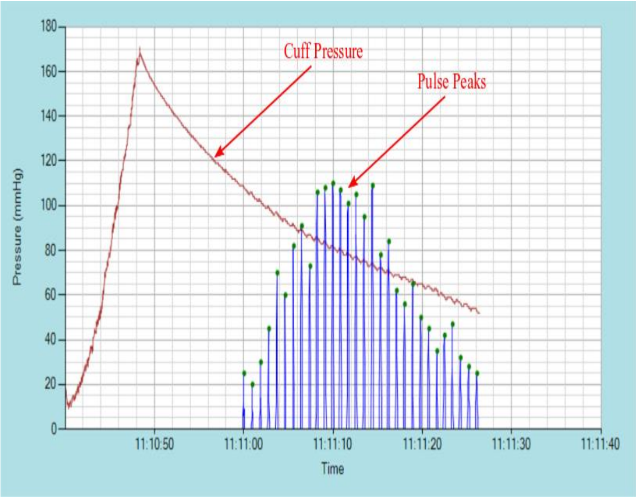


Fig. 4. The cuff pressure and pulse peaks

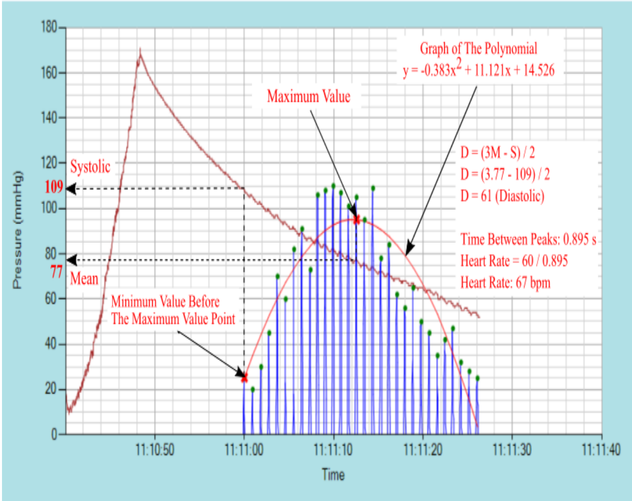


Fig. 5. Pulse peaks, polynomial shape, all blood pressure and heart rate values

When these three equations are solved, a_0 = 14.526, a_1 = 11.121 and a_2 = -0.383. The second-order polynomial of the sample measurement is found as follows:

$$y = -0.383x^2 + 11.121x + 14.526 \quad (7)$$

In this equation, the cuff pressure corresponding to the point where the maximum value is obtained shows the MBP value. Provided that it is before the point where the MBP is obtained, the cuff pressure value corresponding to the point where the minimum value is obtained gives the SBP. Fig. 5 shows the polynomial graph of equation (7) together with the pulse peaks in Fig. 4. Also, in the figure, the points corresponding to MBP and SBP values are given. The formula D = (3M - S) / 2 is used to calculate DBP where MBP, SBP and DBP are defined as M, S and D, respectively [19]. While the air in the cuff is slowly deflated, the mean time values between the pulse peaks are continuously calculated. The value of 60 is divided by the calculated value to determine the number of heart beats per minute. The calculated DBP and heart rate rates by the proposed algorithm are also shown in Fig. 5.

3.4. Developed Prototype

In the present study, the prototype developed for the blood pressure measurement device was designed to perform measurement from the arm. The prototype includes the STM32F4 Discovery Kit, graphic LCD, pressure sensor, mini compressor, directional control valve, battery, and electronic components. The STM32F4 Discovery Kit has a 32-bit STM32F407VGT6 microcontroller [20]. The microcontroller is a product of the STMicroelectronics Company and includes the ARM Cortex-M4 core. It is ARM-based and has a very low power consumption. The microcontroller operates at 168 MHz frequency and the 12-bit ADC units it contains can perform conversions in the range of 0-3 V. It has a 1 MB of program memory and 196 KB internal SRAM. In terms of the digital filter used and the proposed algorithm, the amount of memory and the operating frequency that the STM32F407VGT6 microcontroller has are enough. As the graphic LCD, WG12864C with 128x64 dot resolution produced by the Winstar Company was used [21]. The WG12864C graphic LCD has the KS0108 controller. The MPX5050GP, which produces analogue output and belongs to Freescale Semiconductor, was selected as the pressure sensor [22]. The sensor can measure pressure values up to 50 KPa. The transfer function of it is given in the following equation:

$$V_{out} = 5\ \text{Volt} * (0.018 * \text{Pressure} + 0.04) \pm \text{Error} \quad (8)$$

The mini compressor was used for inflating the cuff. 2/2 (two-way two-position) normally open valve was preferred as directional control valve. It was used to control the air in the cuff. Four AA batteries with alkaline feature were preferred as batteries. Fig. 6 shows the circuit including also electronic components such as the

Table 1. The x_i and y_i values of the measurement in Fig. 4

x_i	y_i	x_i (continued)	y_i (continued)	x_i (continued)	y_i (continued)
1	25	11	108	21	56
2	20	12	110	22	65
3	30	13	107	23	50
4	45	14	101	24	45
5	70	15	105	25	35
6	60	16	95	26	42
7	82	17	109	27	47
8	91	18	78	28	32
9	73	19	84	29	28
10	106	20	62	30	25

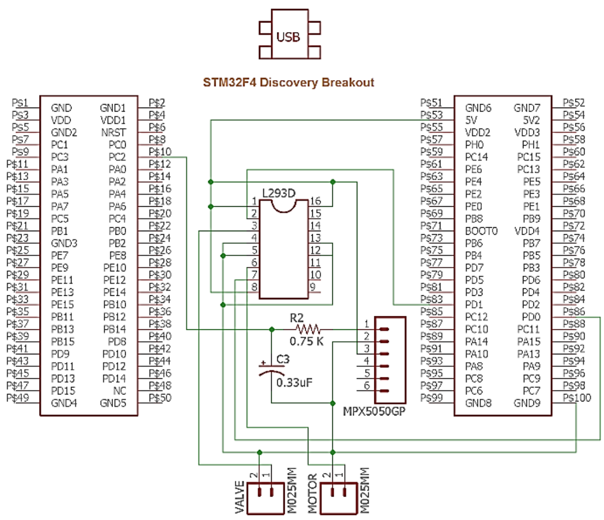


Fig. 6. The circuit STM32F4 Discovery Kit including electronic components

Fig. 7. The developed prototype for blood pressure and heart rate measurement

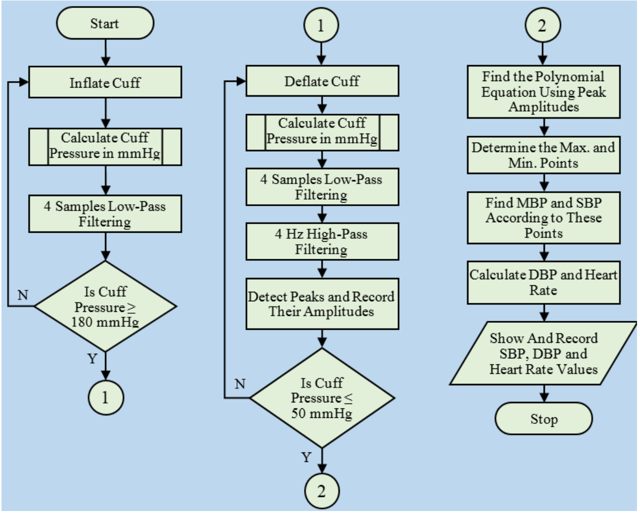


Fig. 8. General flowchart for Normal Measurement Mode

L293D integrated, resistor and capacitor. The printed circuit board was prepared considering the type of this connection, and all the elements were soldered to the corresponding card. Considering the dimensions of the card and other elements (graphic LCD, motor, valve, battery, switches, etc.), a box was designed using the Solidworks software and printed out using a 3D printer. The prototype picture is given in Fig. 7. As seen in the picture, there are two buttons for blood pressure and heart rate measurement. With the first button (Normal Measurement Mode), the values (SBP, DBP and heart rate) are calculated using the proposed algorithm, and the result is shown directly. With the other button (Average Measurement Mode), the values (SBP, DBP and heart rate) are measured three times at intervals of one minute, and the mean values obtained from these measurements are displayed as result.

Fig. 8 shows the general flowchart for the normal measurement mode of the program recorded into the microcontroller. This flowchart was obtained by appropriately assembling the program codes in the temporary interface, created with Microsoft Visual C#, into the STM32F407VGT6 microcontroller. MicroC PRO for ARM software development interface was used for writing and compiling the C-based program, and the mikroProg Suite For ARM was used to record the obtained .hex extension file into the microcontroller.

4. Results

Independent organizations have proposed various protocols to verify/evaluate automatic blood pressure measurement devices. Detailed information about these organizations and the protocols they recommend can be found in [23]-[25]. This study was carried out to show that curve fitting method, a very common numerical analysis method, can be used to estimate blood pressure, but not to develop a commercial product or obtain approval. Therefore, the protocols proposed by these organizations were not adhered. In order to test the measurement accuracy of the developed blood pressure measurement device, a test set consisting of 21 individuals in different age groups was considered to be sufficient. The test set consists of 11 male and 10 female individuals and has an average age of 34.43 ± 10.01 years. Male individuals are between 21 and 56 years of age, and female individuals are between 22 and 55 years of age. The average age for male and female individuals is 33.55 ± 10.01 and 35.40 ± 10.46, respectively. Of the 21 individuals, 13 are over 30 years of age. The test set participants have been divided into two different groups including 10 and 11 peoples. The sphygmomanometer was used for the first measurement of the first group, while it was used for the second measurement of the second group. The developed prototype was used for the second measurement of the first group, while it was used for the first measurement of the second group. Two different measurements were performed by the developed prototype according to the Normal Measurement Mode and the Average Measurement Mode, and the results were recorded separately. The measurements performed using the sphygmomanometer were carried out by the specialist. A minimum of two minutes was used between two measurements in the test procedure.

Various measurements were made by using the sphygmomanometer and the developed prototype on each individual in the test set and the measurement results were recorded separately. Statistical evaluations on them are given in detail in Table 2 for the sphygmomanometer and the developed prototype. The table also include the results obtained for both the Normal Measurement Mode and the Average Measurement Mode of the developed prototype, separately.

The prediction accuracy of the proposed prototype is given in Table 3. The table also includes the mean and standard deviation of the difference between the data measured by the sphygmomanometer and the developed prototype. The prediction accuracy (PA) was calculated by equation (9). The mean (MD) and standard deviation (SD) of the difference were calculated by equations (10) and (11), respectively.

$$PA = \frac{1}{n}\sum_{i=1}^{n} 100 - \left(\frac{|AV_i - MV_i|}{AV_i} * 100\right) \quad (9)$$

$$MD = \frac{1}{n}\sum_{i=1}^{n} |AV_i - MV_i| \quad (10)$$

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (|AV_i - MV_i| - MD)^2} \quad (11)$$

Where n is the number of individuals in the test set, the AV_i is the correct value measured by the sphygmomanometer and the MV_i is the value measured by the developed prototype.

As can be seen from the table, the results are given separately for both the Normal Measurement Mode and the Average Measurement Mode of the prototype. From the point of view of all subjects, the prototype has achieved 94.67% and 92.51% accuracy

Table 2. The statistical evaluation of test results obtained from each individual

Test Group	*Measured Value*	*Sphygmomanometer*		*Developed Prototype*			
				Normal Measurement Mode		*Average Measurement Mode*	
		Mean	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*
Male	*Systolic*	117.55	±12.14	120.18	±12.86	119.82	±13.23
	Diastolic	77.55	±10.42	78.09	±10.06	78.27	±9.78
	Heart Rate	71.91	±8.78	71.55	±8.94	71.91	±9.44
Female	*Systolic*	116.80	±9.47	110.10	±10.51	112.10	±10.47
	Diastolic	76.50	±6.40	76.70	±6.75	76.80	±6.68
	Heart Rate	73.10	±6.03	73.20	±7.07	73.00	±6.32
All	*Systolic*	117.19	±10.69	115.38	±12.61	116.14	±12.35
	Diastolic	77.05	±8.55	77.43	±8.47	77.57	±8.27
	Heart Rate	72.48	±7.43	72.33	±7.95	72.43	±7.93

* All values are given in mmHg.

Table 3. The prediction accuracy, mean and standard deviation of difference for the developed prototype

Test Group	*Measured Value*	*Normal Measurement Mode*			*Average Measurement Mode*		
		Prediction Accuracy (%)	*Mean of Difference (mmHg)*	*Standard Deviation of Difference (mmHg)*	*Prediction Accuracy (%)*	*Mean of Difference (mmHg)*	*Standard Deviation of Difference (mmHg)*
Male	*Systolic*	96.95	3.55	±1.69	96.44	4.09	±1.92
	Diastolic	92.36	6.00	±2.65	93.30	5.27	±2.45
	Heart Rate	98.26	1.27	±1.10	98.49	1.09	±0.94
Female	*Systolic*	92.16	9.30	±4.85	93.80	7.30	±2.06
	Diastolic	92.68	5.60	±2.63	92.79	5.50	±2.27
	Heart Rate	97.04	2.10	±1.37	97.94	1.50	±0.71
All	*Systolic*	94.67	6.29	±4.55	95.18	5.62	±2.54
	Diastolic	92.51	5.81	±2.58	93.06	5.38	±2.31
	Heart Rate	97.68	1.67	±1.28	98.23	1.29	±0.85

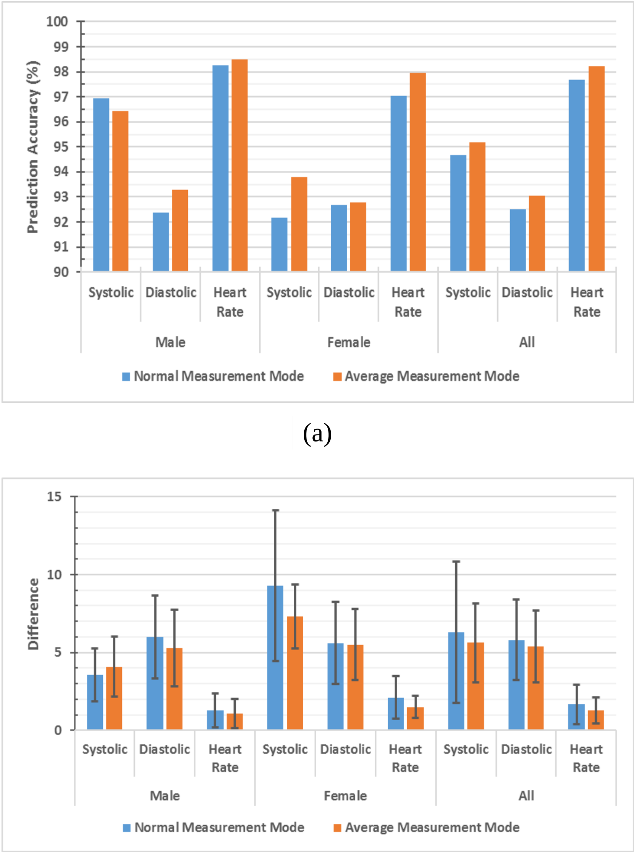
for SBP and DBP values, respectively, in the Normal Measurement Mode. In the same mode, an accuracy rate of 97.68% was observed for heart rate. From the point of view of the same subjects, the prototype has achieved 95.18% and 93.06% accuracy for SBP and DBP values, respectively, in the Average Measurement Mode. In the same mode, an accuracy rate of 98.23% was observed for heart rate.

Table 3 also contains the results obtained for both the Normal Measurement Mode and the Average Measurement Mode of the prototype, separately. As can be seen from this table, from the point of view of all subjects, the difference between the measured data by the prototype and the sphygmomanometer was 6.29 ± 4.55 mmHg and 5.81 ± 2.58 mmHg for SBP and DBP, respectively, in the Normal Measurement Mode. In the same mode, a difference of 1.67 ± 1.28 beats was observed for heart rate. From the point of view of the same subjects, the difference between the measured data by the prototype and the sphygmomanometer was 5.62 ± 2.54 mmHg and 5.38 ± 2.31 mmHg for SBP and DBP, respectively, in the Average Measurement Mode. In the same mode, a difference of 1.29 ± 0.85 beats was observed for heart rate. The data in Table 3 is shown graphically in Fig. 9a and b.

In this study, a second-order polynomial was used to estimate blood pressure values and the above results were obtained. The method of obtaining the second-order polynomial equation was explained on a sample measurement in Section 3.3. However, the degree of polynomial to be used was determined by preliminary experiments on a test set of 14 people. In these preliminary experiments, blood pressure values were estimated using both the second-order and the third-order polynomials. The prediction results obtained by using the second-order polynomial were determined to be closer to the measurements performed with sphygmomanometer. It was also observed that the estimated time for the second-order polynomial was shorter. This is due to the extra calculation cycle and variable amount required for the third-order polynomial. Fig. 10 shows the prediction accuracies obtained for the second- order and the third-order polynomials compared to the measurements performed with the sphygmomanometer. From the point of view of male, female and all subjects, it can be seen from the figure that the higher prediction accuracy is obtained by using the second-order polynomial for both SBP and DBP values.

The prediction accuracy of the curve fitting method proposed for blood pressure estimation was compared with that of the simple hill climbing algorithm [9]. A test set of 10 individuals was used for comparison. SBP and DBP values of each individual were measured with a sphygmomanometer by a specialist. The measurements were performed on the same individuals with the curve fitting and the simple hill climbing methods at intervals of one minute. The results showed that the curve fitting method obtained a higher prediction accuracy of 0.71% and 0.47% for SBP and DBP, respectively, compared to the simple hill climbing method.

The biggest drawback of automatic blood pressure measuring devices using the oscillometric method is that they measure the DBP values with less accuracy than SBP values [26]. This is



(a)

(b)

Fig. 9. a) Prediction accuracy of the developed prototype b) Difference between the data measured by the prototype and the sphygmomanometer

because the detection of the point where the oscillations of the cuff pressure begin to disappear is more difficult than the point where the oscillations begin to appear [9]. In this study, the formula D = (3M - S) / 2 is used for the calculation of DBP where MBP, SBP and DBP are defined as M, S and D, respectively. From the formula, it can be seen that the higher the prediction accuracy of the SBP and MBP values, the higher the prediction accuracy of the DBP value. For this purpose, curve fitting method was used in this study. With this method, the wavy structure of pulse peaks at the cuff pressure was eliminated. Thus, SBP and MBP values were determined with a higher accuracy. This situation was also seen in the prediction accuracy of DBP value.

5. Conclusion

This study was carried out to show that curve fitting method, a very common numerical analysis method, can be used to estimate blood pressure, but not to develop a commercial product or obtain approval. Therefore, an automatic blood pressure measurement device was developed to perform measurement from the arm. The developed blood pressure measurement device was also used as display and control device. The RC and digital filters were preferred as signal processing and filtering methods. Testing the proposed device was carried out using a classical sphygmomanometer in the presence of an expert medical staff. The test set, consisting of 21 individuals, was divided into two groups including 10 and 11 peoples. Results obtained from experiments showed that the developed prototype could attain an accuracy of 94.67% and 92.51% for SBP and DBP values, respectively,

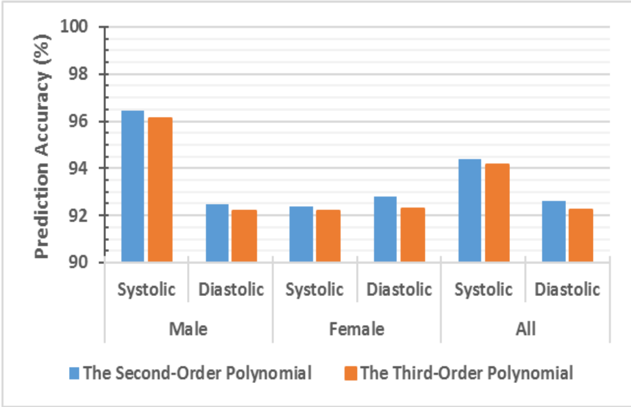


Fig. 10. Prediction accuracy obtained for second and third-order polynomials

compared to those obtained from sphygmomanometers. Also, an accuracy rate of 97.68% was observed for heart rate.

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