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A Circuit Design of a Sensor Amplifier for Improving Blood Pressure Measurement in Telehealth System

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***Abstract*—Hypertension is one of the leading causes of mortality worldwide, increasing the likelihood of developing heart, renal, brain, and other illnesses. Reliable blood pressure measurement is critical because even minor errors can have severe effects on individuals. In this study, we developed a telehealth system that integrates an instrumentation amplifier and band-pass filter circuit to resolve dissipation losses and monitor such conditions, thus improving accurate health parameter measurements. Our prototype was tested on 30 subjects of varying ages for ten cross-validated trials. Quantitative results show that our amplified system was able to outperform high-end digital commercially available instruments with a mean precision of 96.67% (mean arterial pressure), 96.79% (pulse rate), and 99.13% (temperature).**

Keywords*—dissipation losses, e-health, hypertension, instrumentation amplifier, mean arterial pressure, monitoring

I. Introduction

Society needs numerous healthcare solutions that deliver life-saving services. Electronic health (e-health) facilitates health and wellness benefits to patients remotely using telecommunication technologies. Aside from traditional methods, electronic devices can measure various bio-signals such as heart rate, pulse oximetry, temperatures, and other related health parameters. Blood pressure (BP) is a critical vital indicator that requires monitoring due to its link with various health problems, including hypertension [1 – 3] It is a life-threatening medical condition that increases the chance of developing cardiovascular, renal, and cerebrovascular diseases, among other complications. Moreover, it is one of the leading causes of early mortality worldwide, affecting more than a billion people [4]. Statistics show that for an increase of 10mmHg (millimeter mercury) in systolic blood pressure, the relative risk of death rose by 28%, according to a 10-year study from different parts of the globe [5]. Medical professionals highlight the risks that even a slight change in blood pressure can have devastating repercussions.

Regrettably, the accuracy of BP measurement differs significantly amongst devices. The American Heart Association (AHA) advises using a manual mercury manometer for this measurement [6]. Even with a fully calibrated instrument, however, significant measurement error is inevitable [7]. With all of these potential impediments to reliable manual readings, one could conclude that an electronic device is preferable. However, it is not always the case as certifying authorities such as the Food and Drug Administration (FDA) rely on manufacturer's voluntary compliance with requirements [8]. Companies seeking an easy profit are avoiding the procedure of equipment precision testing due to its high cost. These findings pertain to the non-certification of BP equipment sold to hospitals, clinics, and individuals. Additionally, the accuracy issues associated with low-cost and even high-end BP electronic monitors for home users are well known [9 – 11]. Hence, authorities must impose strict testing and mandatory certifications to mitigate and resolve these pressing issues.

Most modern electronic BP devices currently in the market are composed of a pressure sensor, processor, motor mechanism, and cuff. The cuff pressure of the BP sensor can directly measure the magnitude of these pressure pulses. As it reaches the maximum amplitude, the pulses become increasingly significant as soon as the pressure in the cuff is slowly exhausted. If the cuff pressure decreases, it minimizes the occlusion of the artery that causes the pulse amplitude to decay. According to different studies, this dissipating factor causes most electronic BP devices to provide inaccurate results [12], leading to the need to design an additional sensor amplifier [13 - 15]. The use of technology to create tailored interventions for people with hypertension is gaining popularity. In the study of [16], the efficiency of digital technology on hypertension management has a considerable positive influence on BP control. Considering the ubiquity of modern wireless communication devices such as smartphones has made it easier to manage chronic conditions. According to literature, a lot of organizations and researchers have focused on the improvement of these devices for hypertension control.

Telehealth (TH) is a word used to describe electronic applications that leverage information and communication technology (ICT) to provide remote support, flexible and convenient access, and individualized feedback to serve growing health demands [17]. Integration of these systems with pre-existing infrastructures is straightforward and accessible via personal computers, mobile phones, and tablets. Numerous studies have shown that it is a viable option for managing and changing hypertension self-care habits [18 - 22]. Furthermore, it encourages patients, particularly younger generations, who are less likely to undergo lifestyle modification therapy to sustain conscious health behaviors. As a result, the efficacy of existing TH interventions on hypertension self-care using modern technology has to be improved. The primary goal of this study was to design and develop a sensor amplifier for blood pressure sensors in improving the accuracy of critical BP measurements.

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Moreover, a TH system was created with wireless transmission technologies such as a global system for mobile communication (GSM) and radio frequency (RF) for real-time data transmission. It also aims to compare the conventional way of monitoring health parameters between the developed systems.

The paper's main contribution was improving health monitoring in medicine through the design of an instrumentation amplifier as it is beneficial to the public, patients, and health practitioners.

II. METHODOLOGY

A. System Overview

The system primarily concentrates on designing the sensor amplifier of the BP measurement for the TH system. Input components are connected to the designed amplifier, such as pressure sensor, motor pump, and cuff. The process needs to have this crucial amplifier to magnify the signal from the band pass filter to eliminate substantial noises within the signal. A final stage amplifier connects to the output, which is the blood pressure sensor.

After the design of the circuit, the BP's amplifier is connected with other inputs such as the AC source, power supply, body temperature sensor, and pulse rate sensor. Such inputs are processed and read through the microcontroller serving as the heart of the system. The controller then sends the data to the GSM and Zigbee, reflecting the output through an LCD display.

B. Methods and Procedures

This section presents the processes and methods adopted in gathering data needed for the research work. It includes hardware and software development, and other related methods to determine the effectiveness of the study. Figure 1 shows the block diagram of the methodologies used to design and implement the circuit amplifier design.

The process flow diagram consists of the sensor amplifier's design, the TH system's design and fabrication, simulation of the sensor amplifier, and the tests evaluation.

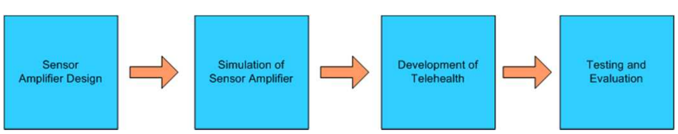

Fig. 1. Process flow diagram

C. Sensor Amplifier Design

Figure 2 shows the schematic principle operation of the system initially based on Karplus and the Texas Instrument handbook using a Wheatstone bridge sensor [23]. The amplifiers consist of an instrumentation amplifier, a low-pass filter, and a final stage amplifier. These three additional electronic components are specifically design to solve the occurrence of signal losses as observed for the wide array of electronic BP measuring devices available on the market. It is crucial to solve the dissipation losses encountered as observed on commercially available electronic measuring devices.

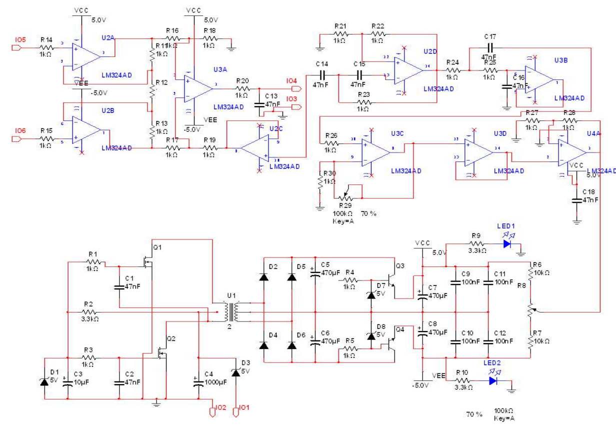

Fig. 2. Schematic diagram of the sensor amplifier

D. Operational Amplifier Selection

A critical part of the design is the selection of operational amplifiers (op amps). Most op amps will work for the design but we intentionally selected the LM324 instrument amplifier (IA) [24] comprised of four operational amplifiers on a single chip to minimize the amount of wires to construct the circuit. It also has a proven track record in many complex electronics designs having a notable maximum gain and has a saturation level at $V_{cc} - 1.5$ V. If the product of the input and the gain exceeds the threshold, the op-amp will enter saturation and provide an incorrect output. It is the primary reason for the selection of the component.

E. Resistor Value Selection

A typical IA has seven resistors. Selection of resistor values is identified through using a transfer function using the equation of:

$$V_{out} = (V_1 - V_2)(R_2/R_1)(1 + (2R_5)/R_G) \quad (1)$$

This is true if R_5 equaled R_6, R_2 matches R_4, and R_1 equals R_3. However, if $R_6 = R_5 = R_1 = R_4 = R_2 = R$, this transfer function could be reduced further, Thus, the formula is:

$$V_{out} = (V_1 - V_2)(1 + 2R/R_G) \quad (2)$$

Based on the equation, we select the value of R ranging from 25KOhm to 1MOhm. Figure 3 shows the schematic diagram of IA.

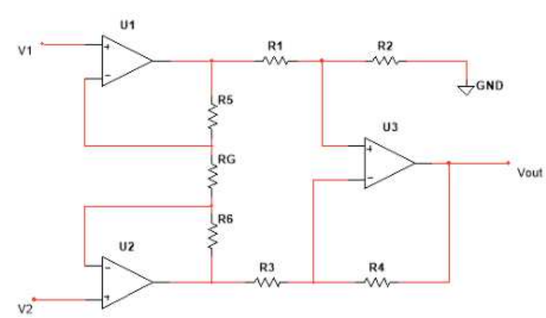

Fig. 3. Instrumentation amplifier (IA) circuit

F. Gain Calculation and Testing IA

A streamlined transfer function based on Equation 2 enables the overall gain to be determined by a single resistor (R_G). A low value resistor for R_G results in a higher gain, whereas a bigger resistor leads in a lower gain.

We run the tests using MultiSim software to test the circuit to verify and characterize the design's performance by setting the function generator to 500m *VPP SIN* wave at 1 kHz and inputting it to *V1* (see Figure 3). To check the gain of an instrumentation amplifier, an oscilloscope probe must be placed on the function generator and another on the output amplifier.

Figure 4 shows the input and output simulation testing waveforms with an input offset equal to 172.991µ while the output offset is -172.934µ with only 0.057 absolute difference.
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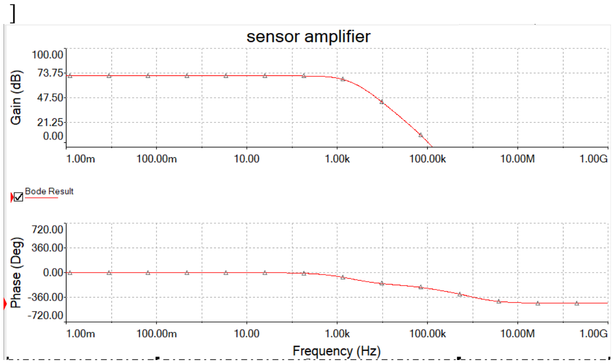

Fig. 4. Simulation of gain and phase

G. Band-Pass Filter Design

A band-pass filter was adapted to capture the cuff pressure and pulse wave signals from the noise signals. This design is adapted to adjust the appropriate signal levels and as an input to the analog-to-digital conversion circuits. The filter's circuitry is composed of 4-stage operational amplifier to properly detect pulse signals and remove further interferences. Figure 5 shows the band-pass filter (BPF) for the pulse wave signals processing.

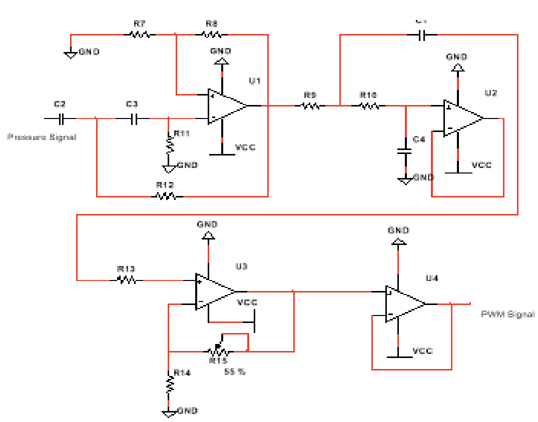

Fig. 5. Band-pass filter design

H. Final Stage Amplifier

A signal coming from a BPF is weak and needs amplification at the final stage to further avoid dissipation losses. This is significant to attain accurate reading. Figure 6 illustrates the design of the final stage amplifier.

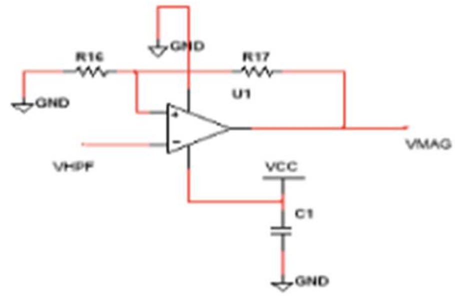

Fig. 6. Final stage amplifier design

I. Design and Development of Telehealth System

Figure 7 and Figure 8 show the diagram of the system's setup, including both hardware and software components. Two major components, such as the transmitting and receiving units, handle the system's essential operation. The transmitting unit serves as the input, which is composed of medical sensors that measure a person's specific health parameters. An Arduino microcontroller manages the sensors and data acquisitions are displayed on the liquid crystal display (LCD) and transmitted to the receiving unit. The two units in the system are the host computer and mobile phone.

Through Zigbee technology, the acquired data are accessed through wireless medium to the host computer for storage purposes. Furthermore, the data are received through a mobile phone using short-message sending (SMS). Moreover, the figure shows the system operation along with the interconnections of the components involved in the system. The body temperature sensor, pulse rate sensor, and blood pressure sensor served as the system's input while the LCD, computer, and mobile phone served as the output at which the acquired data are received and displayed.

We utilized a ZigBee router and a GSM module as transmitters for their known flexibility while the ZigBee coordinator connected to the computer through the Arduino and the mobile phone serves as the receivers.

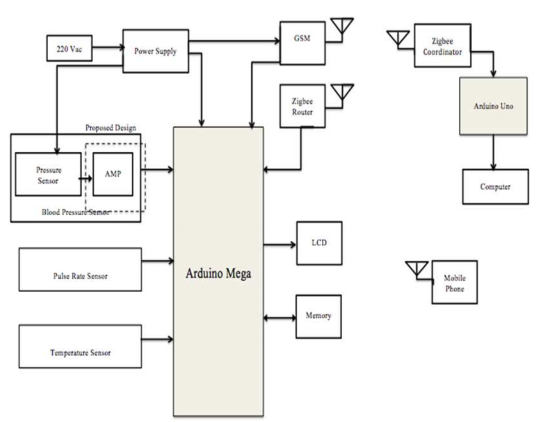

Fig. 7. Block diagram of the Telehealth system

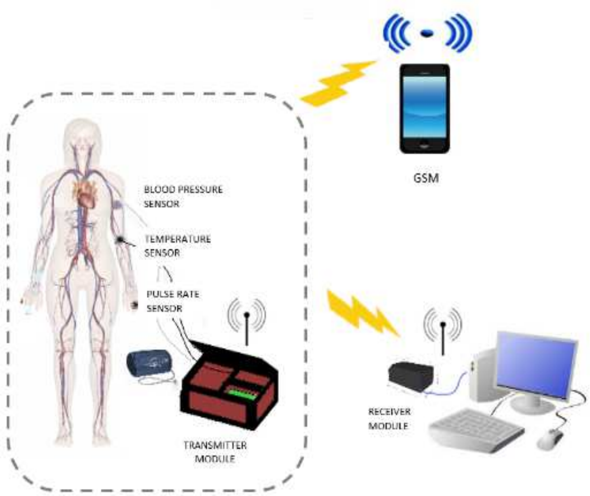

Fig. 8. Telehealth system's setup

J. Testing and Evaluation Metrics

To validate the measurement accuracy of the design, we performed cross-validated trials for three age brackets (8 – 16, 17 – 29 & 30 and above). We selected thirty respondents for each age bracket and recorded their average mean arterial pressure (MAP) [25], temperature, and pulse rate ten times on each trial using a conventional calibrated manual manometer conducted by trained professionals to set the unbiased baseline measurements. These results were then compared to commercially available high-end digital instruments and the records made by our enhanced prototype. Three standard-based evaluation metrics were used, such as root mean squared error (RMSE) [26], mean absolute percentage error (MAPE), and mean bias error (MBE) for results validation [27]. Equations 3, 4, and 5 express the details of the formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(t_i - p_i)^2}{N}} \quad (3)$$

$$MAPE = \frac{\sum_{i=1}^{N}\left|\frac{t_i - p_i}{p_i}\right| x\ 100}{N} \quad (4)$$

$$MBE = \frac{\sum_{i=1}^{N}\left|\frac{t_i - p_i}{p_i}\right|}{N} \quad (5)$$

where t_i is the cross-validated health parameter measured values, p_i is the benchmarked results of a commercial digital instrument and the developed prototype, and *N* is the number of trials.

We have purposely selected the scaled-dependent RMSE as it is a remarkable all-purpose error statistics capable of examining error differences. MAPE is another error metrics that are not scale-dependent and compares results at various scales. Finally, the MBE primarily determined if the measurement results are underestimated or overestimated.

III. Results

This section investigates and assesses the accuracy of health parameter data measured using conventional (C), digital (D), and our prototype (P) instruments using the amplifier design. The following subsections show the different results.

A. Mean Arterial Blood Pressure (MAP) Readings

Table 1 shows the comparative blood pressure measurements compiled from the conventional, commercial, and our developed prototype.

TABLE 1
Mean Arterial Pressure Comparative Test Results

Trial	Age Brackets								
	8 - 16			17 - 29			30 and above		
	C	D	P	C	D	P	C	D	P
1	90	87.7	88.6	90	71	82.1	94.4	101.7	95.8
2	87.7	79.3	84.1	86.67	88.3	88.5	87.7	80.3	85.4
3	74.4	71.7	78.3	78.89	78.1	81.3	92.2	94.5	91.3
4	90	86.6	87.7	87.78	87.7	85.2	82.2	81.7	76.7
5	82.2	78.5	78.6	77.78	67	81.6	91.1	94.4	91.4
6	83.3	80.3	80.4	74.44	71.7	74.7	85.5	84.5	89
7	77.7	76	79.8	92.22	87.8	84.5	78.8	81.2	79.7
8	88.8	82.8	85.2	78.89	80.3	78.3	81.6	78.1	76.6
9	85.5	82.7	86.5	87.78	81.8	84.3	92.2	93.3	91.8
10	77.7	76.5	75.7	92.22	87.5	85.3	88.8	88.2	90
RMSE		4.06	**2.81**		7.53	**4.61**		3.80	**2.79**
MAPE		4.14	**3.18**		6.01	**4.27**		3.32	**2.52**
MBE		-3.52	-1.24		-4.54	-2.08		0.34	-0.68

It demonstrates that our prototype produces an accurate measurement compared to a commercially available blood pressure device by obtaining lower RMSE outcomes for all age brackets of 2.81, 4.61, and 2.79. In addition, it achieved better MAPE values of 3.18, 4.27, and 2.52. MBE results show that our prototype, on average, underestimated the baseline readings by only -1.33.

B. Pulse Rate Readings

The comparison of pulse rate data taken from the conventional, digital, and our designed prototype is shown in Table 2. Our prototype beats a commercially available digital pulse rate monitoring instrument with reduced RMSE scores of 2.01, 6.54, and 2.31. The results indicated our amplifier's design capacity in achieving MAPE values of 2.15, 5.60, and 1.88. MBE records show that our prototype deprecated the baseline measurements by only -2.28.

TABLE 2
Pulse Rate Comparative Test Results

Trial	Age Brackets								
	8 - 16			17 - 29			30 and above		
	C	D	P	C	D	P	C	D	P
1	82.6	87.6	83	72.6	88	70.3	101	104.6	100.6
2	75.6	76.3	76.1	67	89.6	69.3	72.6	77	74.3
3	77.3	75	76.3	77.3	82	74.6	80.3	85.3	83.6
4	82.3	79.6	79.6	93.3	98.3	90.6	84.8	84.8	84.4
5	72.3	69	68.6	83.3	80.3	81.3	91.3	93.3	90.6
6	67.3	64	66.3	98.3	93.67	88.3	101	105.3	101.3
7	79	74.6	76.6	103	93	92	74.6	76.6	73.6
8	77.6	75.3	75.4	102	127.3	94.6	75.3	75.3	74.1
9	71.3	70	71.2	92.6	95	91	94.3	90.6	88.3
10	80.6	76.3	78	101.6	101.6	90.6	71.6	70.6	70.6
RMSE		3.23	**2.01**		12.53	**6.54**		3.13	**2.31**
MAPE		3.83	**2.15**		11.17	**5.60**		3.03	**1.88**
MBE		-1.82	-1.48		5.77	-4.84		1.66	-0.54

C. Temperature Readings

The temperature measurements accumulated from the conventional, commercial, and our prototype are summarized in Table 3. Our device surpasses a commercially available pulse rate apparatus in terms of performance and has a lesser RMSE evaluation of 0.23 and 0.51 except for age bracket 30 and above (0.48). The results revealed our design’s advantages in achieving MAPE values of 0.54, 1.10, and 0.96. According to MBE results, our prototype underestimated the measurements by an average of -0.083.

TABLE 3
TEMPERATURE COMPARATIVE TEST RESULTS

Trial	Age Brackets								
	8 - 16			17 - 29			30 and above		
	C	D	P	C	D	P	C	D	P
1	36.1	36.3	36	36.3	37	36.2	36.9	37	36.2
2	36.3	36.2	36.2	36.2	37	36.1	36.3	36.8	35.1
3	36.8	37	36.9	35.4	36.7	36.6	37	36.8	37
4	37	36.7	36.6	36	36.3	36.1	37.3	37.5	37
5	36.4	36.6	36.5	36.4	36.8	36.7	35.7	36.2	36.7
6	35.8	36	36.1	36.2	36.8	35.8	36.8	36.4	36.7
7	36.3	36.7	36.2	36.3	36.6	35.9	37	37.4	37
8	36.2	36.8	36	37.1	36.7	36.6	37.2	36.6	37.5
9	36.7	36.3	36.3	36.7	36.8	36	35.8	36	36
10	36.6	36.5	36.4	36.7	36.8	36.9	36	37	37
RMSE		0.30	**0.23**		0.60	**0.51**		**0.48**	0.49
MAPE		0.74	**0.54**		1.38	**1.10**		1.12	**0.96**
MBE		0.09	-0.01		0.42	-0.04		0.17	0.02

IV. DISCUSSIONS

This research demonstrated the advantages of the amplifier circuit design in improving the accuracy of health-related parameter measurements through extensive testing. The quantitative results show that our prototype using the amplifier circuit design outperforms high-end commercially available digital instruments with a precision of 96.67% (blood pressure), 96.79% (pulse rate), and 99.13% (temperature). Our findings clearly illustrate that integrating additional amplifiers to the test instruments coupled with circuit filter design significantly improves overall readings. It reduces error rates by a collective mean of 1.39%. Furthermore, it demonstrates that the dissipation losses in signals were intuitively compensated by the prototype. The study’s findings are at par with the works of [28 – 34] in digital measurements of health parameters. Similar to any vital signs measuring device, improper connection of the sensors to the appropriate body parts can result to inaccurate readings. Also, unnecessary movements and action of an individual during testing specifically for the blood pressure and pulse rate sensor can greatly affect the quantitative results. Thus, standard operating procedures must also be considered in using our health measuring device.

V. CONCLUSIONS AND FUTURE WORKS

A sensor amplifier based on an instrumentation amplifier with a band-pass filter was designed and deployed in the TH system. The data gathered determined the prototype's accuracy compared to commercially available digital instruments. Quantitative results demonstrated its capabilities in measuring blood pressure and other health parameters significantly closer to traditional devices readings. It indicates that the amplification of the signal plays a crucial role in obtaining accurate results. Our research is far from perfect as a full-fledged system and more improvements can be done. As for the future direction of the research, the authors will expand the system's feature by adding more sensors to monitor health-related parameters, such as oxygen saturation, glucose, electrocardiogram (ECG), electromyography (EMG), and galvanic skin response. In addition, a transformer-less power supply for weight reduction and a smaller-sized microcontroller and transmitting unit will be explored to make the system as portable as possible.

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A Circuit Design of a Sensor Amplifier for Improving Blood Pressure Measurement in Telehealth System

Publisher: IEEE

Maurine C. Panergo ; Febus Reidj G. Cruz ; Renato R. Maaliw **All Authors**

Abstract

Document Sections

I. Introduction

II. Methodology

III. Results

IV. Discussions

V. Conclusions and Future Works

Authors

Figures

References

Citations

Keywords

Metrics

Abstract:
Hypertension is one of the leading causes of mortality worldwide, increasing the likelihood of developing heart, renal, brain, and other illnesses. Reliable blood pressure measurement is critical because even minor errors can have severe effects on individuals. In this study, we developed a telehealth system that integrates an instrumentation amplifier and band-pass filter circuit to resolve dissipation losses and monitor such conditions, thus improving accurate health parameter measurements. Our prototype was tested on 30 subjects of varying ages for ten cross-validated trials. Quantitative results show that our amplified system was able to outperform high-end digital commercially available instruments with a mean precision of 96.67% (mean arterial pressure), 96.79% (pulse rate), and 99.13% (temperature).

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Society needs numerous healthcare solutions that deliver life-saving services. Electronic health (e-health) facilitates health and wellness benefits to patients remotely using telecommunication technologies. Aside from traditional methods, electronic devices can measure various bio-signals such as heart rate, pulse oximetry, temperatures, and other related health parameters. Blood pressure (BP) is a critical vital indicator that requires monitoring due to its link with various health problems, including hypert g medical condition that increases the chance of developi rovascular diseases, among other complications. Moreover, it is one of the leading causes of early mortality worldwide, affecting more than a billion people [4]. Statistics show that for an increase of 10mmHg (millimeter mercury) in systolic blood pressure, the relative risk of death rose by 28%, according

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Maurine C. Panergo, Febus Reidj G. Cruz, Renato R. Maaliw III
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