A Comprehensive Framework for Wearable Module for Prenatal Health Monitoring and Risk Detection

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***Abstract*—This paper proposes a modular health monitoring system for pregnant women, encompassing vital sign monitoring such as temperature, heart rate, oxygen saturation, blood pressure, and introduces a noninvasive Near-Infrared (NIR) blood glucose monitoring system, employing a 2nd order polynomial regression model for enhanced accuracy. Rigorous evaluation using commercially available devices validates the system's reliability. Leveraging Internet of Things (IoT) capabilities, the system enables remote monitoring, fostering real-time connectivity between healthcare providers and expectant mothers. An integrated SMS alert system enhances communication in critical situations. Addressing the challenge of differentiating between normal movements of mother and fetal kicks, the paper introduces a hybrid algorithm utilizing two Inertial Measurement Units (IMUs) for precise fetal kick detection. This comprehensive system offers a holistic solution to prenatal care, with potential implications for improving maternal and fetal health outcomes.**

Keywords—Health monitoring, Modular, Pregnant women, IoT, Fetal kick detection

I. INTRODUCTION

Regular health checkup of a pregnant woman is of utmost importance as the risks associated with pregnancy can be seriously life-threatening. The maternal mortality ratio (MMR) is an important metric in public health that assesses the number of women who die from pregnancy-related causes per 100,000 live births. The maternal mortality ratio (MMR) covers deaths resulting from pre-existing medical conditions worsened by the physical effects of pregnancy, alongside complications directly associated with pregnancy or its management. In comparison to more developed nations, less developed countries typically exhibit higher MMRs. The increased MMR in developing nations can be attributed to various factors such as inadequate sanitation, poverty, limited education, insufficient prenatal care, inadequately trained birth attendants, restricted access to quality healthcare services, and socio-economic disparities. Geographical isolation, cultural practices, and scarce resources in these regions may additionally impede women's access to medical facilities, potentially leading to higher maternal mortality rates due to insufficient prenatal care, lack of professional assistance during childbirth, or delayed emergency obstetric care when facing complications. According to data from the World Bank and the World

World Health Organization (WHO), Bangladesh recorded an estimated maternal mortality ratio of 173 deaths per 100,000 live births in 2017 [1]. Moreover, WHO revealed that nearly 800 women died due to preventable health issues related to pregnancy and childbirth in 2020. The high mortality rate in Bangladesh is attributed to the lack of effective infrastructure for regular health checkups of pregnant women. Reducing maternal mortality and consistent monitoring are important aims in worldwide healthcare systems. Sustaining a low MMR demands continuous monitoring of the health of pregnant women. The proposed solution aims to build a smart health monitoring system designed particularly for pregnant women, focusing mainly on vital health indicators. The main aim is to predict health issues and develop a reliable alert system for possible pregnancy-related emergencies. The project focuses on designing a cost-effective, non-invasive device that connects with smartphones for consistent monitoring while maintaining the patient's health safety while ensuring the accuracy of each specific parameter.

II. RELATED WORK

In this segment, we provide a concise overview of recent advancements in healthcare systems in the realm of the Internet of Things (IoT) designed explicitly for monitoring maternal health. Numerous researchers have explored the implementation of remote monitoring services; however, most of these designs employ survey-based methodology and manual data input [2]. Lopez et al. proposed a wearable technology model to monitor and control hypertension during pregnancy. The model involves a wrist-worn wearable sensor device that gathers data (blood pressure, heart rate, steps) every 30 minutes while manually inputting other parameters [3]. However, it exclusively targets hypertension symptoms and does not monitor other vital health parameters such as temperature, oxygen saturation, and blood glucose levels. Troyee et al., in their study, introduced a wearable gadget comprising several sensors, including a non-intrusive glucose rate detection system utilizing a 940nm NIR LED. Additionally, they created a method for detecting sudden falls by employing an accelerometer [4]. Yet the proposed design lacks many other vitals, and the system's accuracy needs to be validated in the proposed design. Two researchers have proposed a model for gathering health data from a pregnant mother to assess maternal and fetal well-being. Collected data includes respiration rate, body temperature, fetal movement, phonocardiogram (PCG), ECG, and photoplethysmography (PPG). These are processed for real-time visualization in an app [5]. Nevertheless, the paper's limitations include the absence of emergency notifications and the need for additional maternal health data.

Kumar et al. proposed an architecture for health monitoring during pregnancy, considering the need to adapt the system based on collected health data [6]. Priyanka et al. developed a health monitoring system for pregnant mothers that uses sensors and a microcontroller to track vital parameters such as Blood Pressure, Heart rate, Temperature, and Fetal motion [7]. However, their model is not wearable, unlike our developed module, which is crucial for instant emergency detection, a key aspect in monitoring devices for immediate response. The paper detects fetal motion with an abdomen-placed accelerometer across three axes but lacks a specific algorithm to differentiate fetal movements from the mother's regular motions.

Lyu et al. introduced a mobile vital sign monitoring system on Android for pregnant women, employing multi-communication fusion. The framework incorporates sensors, a speech module for doctor-patient communication, and key components like the fusion controlling module, wireless band manager, and multiple vital signs server. However, the details could be more specific, and the design is mainly conceptual [8]. Regarding the data handling of pregnant women data, a group of researchers introduced a database management system to monitor the health checkup progress of pregnant women who are registered in their healthcare database [9]. Rahman et al. proposed the layout of a web platform that allows patients and doctors to view health data and set up a special helpline number to call for quick help [10]. However, the specifics of the architecture need to be described. A similar work regarding the use and implementation of databases has been done by Ahmed et al., where a medical dataset has been created by merging various data on pregnant women collected from various clinics. This sort of database management can help clinics, doctors, and policymakers take steps to improve the infrastructure [11]. However, existing research relies on hospital and clinic data for database management, limiting insights for improving infrastructure. However, there needs to be more home-monitored data.

From the existing literature, it is evident that considerable potential exists for the development of a specialized vital sign monitoring device to monitor pregnant women, complemented by an efficient remote monitoring system. Additionally, a thorough examination of the accuracy of the implemented system is imperative. Notably, shortcomings observed in prior designs highlight the need for a proper fetal movement detection algorithm. In response to these identified deficiencies, we propose this design of a cost-effective modular health monitoring system specifically designed for maternal health monitoring. This innovative system includes vitals monitoring such as temperature, heart rate, oxygen saturation, blood pressure, blood glucose, and features such as fall detection. It introduces an innovative algorithm for fetal kick detection, achieved through the usage of data from a secondary Inertial Measurement Unit (IMU).

III. Proposed Methodology

In designing the health monitoring system dedicated to pregnant women, our focus is on selecting vital parameters critical to maternal and fetal well-being. We considered vital signs such as temperature, oxygen saturation, heart rate, blood pressure, and blood glucose. Additionally, we aimed to track fetal movement and detect unwanted falls. Our central processing unit is the ESP-32s microcontroller, chosen for its ability to collect and send data over the cloud through Wi-Fi.

To get accurate temperature readings, we selected the DS18b20 sensor. For monitoring oxygen saturation and heart rate, we used the MAX30100 sensor which is working principle is pulse oximetry. Addressing the discomfort of invasive blood glucose measurement, we propose a non-invasive solution using infrared light absorption technique. We have utilized a NIR 940mm led and a photodetector to detect the blood glucose level. The light absorbed by the glucose enriched blood is different from blood with less glucose level. This allowed us to measure the blood glucose level by comparing the output from the photodetector. However, in order to mitigate the noises, we have enclosed the glucose measurement system in a black box so that it cannot be affected by the external lights. This method allows continuous monitoring without the pain associated with traditional techniques which involves poking a needle every time we want to measure, serving as an early warning system for potential issues. For the blood pressure monitoring, we have used an off the shelf blood pressure monitoring device equipped with an EEPROM which stores the reading of the measurements. The way the Blood pressure machine and the EEPROM chip communicates is by utilizing the I2C protocol. In order to monitor the blood pressure value, the off the shelf blood pressure machine was modified and the button to start the blood pressure measurement was mimicked by the main microcontroller. Further the valve of the blood pressure machine was monitored to mark the completion of measuring blood pressure. Once the blood pressure measurement is done the BP machine tries to send the data to the connected EEPROM chip, but the microcontroller is hooked with that EEPROM line acting as a slave device which listens for any incoming data. So, when the BP machine sends blood pressure data to the EEPROM to store, the ESP-32-S which is acting as a slave device in the I2C bus listens for the incoming bits and processes it to get the blood pressure reading.

The fall detection algorithm works with the use of acceleration parameters of MPU6050. If a sudden change is seen in the acceleration, then it is considered as the person has fallen. However, in order to mitigate the number of false detections, our system checks for multiple peaks in acceleration value within a very short period. If multiple peaks are found it is flagged as a fall detection.

In order to get the fetal movement, we have used another IMU named ADXL335. The IMU is used as the main unit dedicated to recognizing fetal movement. The main problem with fetal movement detection was to differentiate between the acceleration due to walking and fetal movement. In this methodology we propose the use of two IMU units. The MPU6050 which is dedicated for fall detection also works as a reference IMU for the fetal movement detection. When an abrupt change is seen in the acceleration of the ADXL335 data the system checks with the other IMU which is MPU6050's data. If it is seen that after subtracting the MPU6050's acceleration value from the ADXL335's there is still a noticeable increase in the acceleration value, then the system flags it as a fetal movement. Both the IMU's give the output in terms of acceleration of x, y, and z axis. In order to calculate the total acceleration, the following equation 1 is used with the following terminologies:

$A_t = Total\ Acceleration$

$A_x = \text{Acceleration in X} - \text{axis}$

$A_y = \text{Acceleration in Y} - \text{axis}$

$A_z = \text{Acceleration in Z} - \text{axis}$

$$A_t = \sqrt{(A_x)^2 + (A_y)^2 + (A_z)^2} \tag{1}$$

For both the IMUs in order to calculate the orientation the slope of the acceleration's data is utilized to derive the additional features such as pitch, roll and yaw. The following equations 2, 3 and 4 are used to calculate the parameters.

$$Roll = (\frac{180}{\pi}) \times \tan^{-1}\left(\frac{A_x}{\sqrt{{A_y}^2+{A_z}^2}}\right) \quad (2)$$

$$Pitch = (\frac{180}{\pi}) \times \tan^{-1}\left(\frac{A_y}{\sqrt{{A_x}^2+{A_z}^2}}\right) \quad (3)$$

$$Yaw = (\frac{180}{\pi}) \times \tan^{-1}\left(\frac{A_z}{\sqrt{{A_x}^2+{A_y}^2}}\right) \quad (4)$$

In order to enable remote monitoring over the cloud, we have used the Blynk Cloud platform, an MQTT (Message Queuing Telemetry Transport) platform suitable for data exchange between constrained devices and server applications. Our system transmits user data after each 30-second interval except for blood pressure, activated manually or after a user-defined interval from the IoT server. Apart from the remote capability, the system incorporates an alert system. The alert system is based on the thresholds set in the main processing unit. Whenever any vital sign shows any anomaly or if there is a fall detection, the system triggers the alert system, which consists of a push notification to the remote device and SMS to a predefined number using an API, reducing the number of components involved. Our proposed methodology integrates established sensors with innovative algorithms, providing a comprehensive solution for maternal health monitoring, making it an accessible and effective system for expectant mothers. The architecture of the hardware is shown in figure 1.

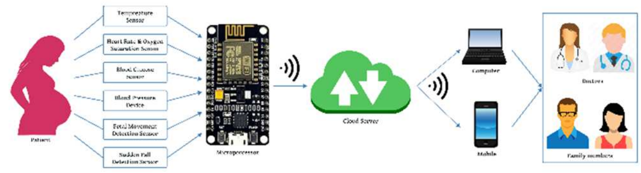

Fig. 1. System architecture of the proposed design

IV. System Implementation

Following meticulous individual testing of each component, we have undertaken the design and assembly of a Printed Circuit Board (PCB), aligning with our proposed methodology. This comprehensive testing phase ensures the optimal functionality of each component before integration into the final system. In particular, we have employed soft and flexible wiring for the connecting wires associated with the sensors. The developed final device is depicted in the following figure 2.

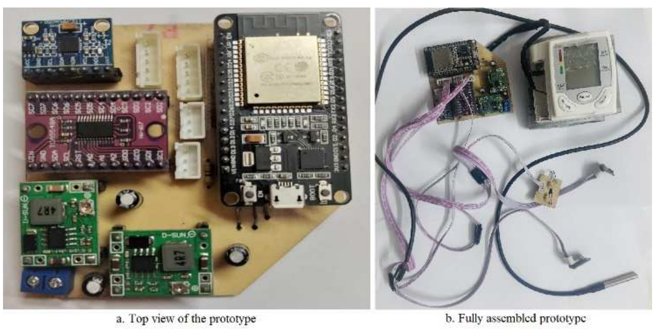

Fig. 2. Developed prototype of the proposed design

As per our proposed methodology, the designed user interface of the mobile application for maternal health monitoring is shown in Figure 3a. The system can also store the data in the database, and if the doctor wants to analyze the historical data, he/she can do it using the designated portal designed for the doctors. The designed webpage for the doctors is illustrated in the following figure 3b.

Fig. 3. Developed mobile application and webpage

One of the major concerns for such health monitoring devices is the placement of the device. We have placed the device in a pouch around the user's waist, and the sensors that need to be placed on the fingers or underarms are connected to the main processing unit using wires. The tentative placement of the sensors is shown in the following figure 4.

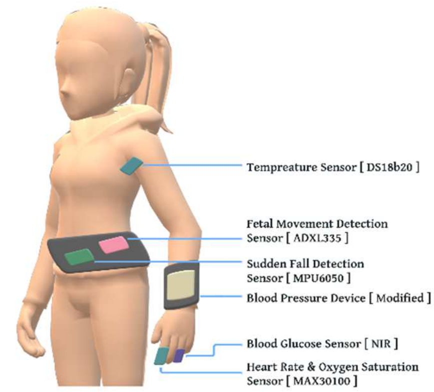

Fig. 4. Tentative placement of the sensors

V. Result and Analysis

Following the implementation of the proposed prototype, it became imperative for us to conduct a thorough evaluation of the device's accuracy. To validate vital monitoring parameters such as Temperature, Heart Rate, Oxygen Saturation, and Blood Pressure, the system underwent evaluation with a total of four volunteers. For each volunteer, a comprehensive set of five readings was obtained, resulting in a total of 20 readings for each monitored parameter for subsequent error analysis. The findings of the error analysis are discussed in the following subsections.

The following notations are used in all the tabular representations:

DFP - Data from the prototype
DFCD - Data from commercial device
SE - Squared Error
MSE- Mean Squared Error
MAPE- Mean Absolute Percentage Error

A. Accuracy Analysis of Temperature

For the accuracy analysis, the reference device that has been used is a commercially available thermometer. The error metric used in the analysis is the Mean Squared Error.

TABLE I. TEMPERATURE ACCURACY ANALYSIS

Volunteer	DFP	DFCD	Error	SE
1	97.485	97.5	0.015	0.0002
	97.686	97.7	0.014	0.0002
	97.554	97.5	-0.054	0.0029
	97.525	97.5	-0.025	0.0006
	97.456	97.4	-0.056	0.0031
2	98.813	98.9	0.087	0.0076
	99.101	99.0	-0.1	0.0102
	99.283	99.2	-0.083	0.0069
	98.959	98.9	-0.059	0.0035
	99.132	99.1	-0.032	0.0010
3	98.315	98.4	0.085	0.0072
	98.936	98.9	-0.036	0.0013
	99.339	99.4	0.061	0.0037
	98.753	98.7	-0.053	0.0028
	98.991	98.9	-0.091	0.0083
4	97.451	97.4	-0.051	0.0026
	97.363	97.3	-0.063	0.0040
	97.657	97.7	0.043	0.0018
	97.232	97.2	-0.032	0.0010
	97.91	97.9	-0.01	0.0001
			MSE	0.0035

Based on the Table I data, it is found that the implemented temperature measurement system has a Mean Squared Error of only 0.0035, and the results are graphically presented in the following figure 5.

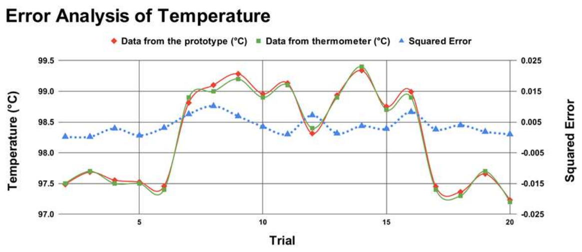

Fig. 5. Error analysis of the prototype and thermometer for temperature

B. Accuracy Analysis of O2 Saturation and Heart Rate

For the accuracy analysis, the reference device used is a commercially available pulse oximeter. The error metrics used in the analysis is the MSE for both the vitals.

TABLE II. O2 SATURATION AND HEART RATE ACCURACY ANALYSIS

Volunteer	Oxygen saturation			Heart rate		
	DFP	***DFCD***	***SE***	***DFP***	***DFCD***	***SE***
1	99	98	1	87	85	4
	99	99	0	88	90	4
	98	99	1	84	85	1
	100	99	1	91	90	1
	99	98	1	87	87	0
2	97	99	4	93	94	1
	99	98	1	96	93	9
	96	97	1	90	88	4
	99	100	1	91	91	0
	98	98	0	90	88	4
3	99	98	1	82	83	1
	100	98	4	88	87	1
	100	100	0	81	83	4
	99	98	1	85	85	0
	99	100	1	83	81	4
4	98	97	1	87	88	1
	99	99	0	91	89	4
	98	97	1	93	92	1
	96	97	1	88	89	1
	99	98	1	89	87	4
		MSE	1.1		MSE	2.45

Based on Table II data, it is found that the implemented oxygen saturation and heart rate measurement system has a Mean Squared Error of only 1.1 and 2.45, respectively. Both the vitals follow the data trend of the commercial device, which can be seen from the following figure 6 and figure 7.

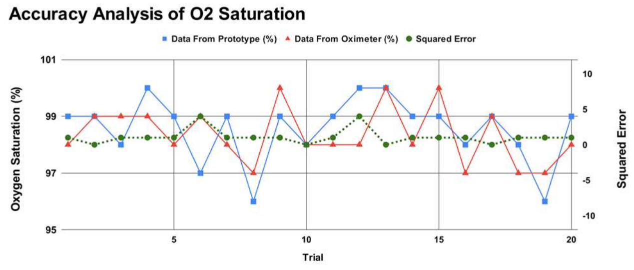

Fig. 6. Error analysis of the prototype and oximeter for O2 saturation

Fig. 7. Error analysis of the prototype and oximeter for heart rate

C. Accuracy Analysis of Blood Pressure

For blood pressure monitoring, the data taken is already from a commercially available blood pressure machine. However, as the machine is modified so, another commercial device is used as a reference device to analyze the data of the developed prototype.

TABLE III. BLOOD PRESSURE ACCURACY ANALYSIS

Volunteer	Systolic blood pressure			Diastolic blood pressure		
	DFP	***DFCD***	***Error %***	***DFP***	***DFCD***	***Error %***
1	119	125	4.80%	71	75	5.33%
	134	142	5.63%	91	94	3.19%
	119	124	4.03%	76	81	6.17%
	132	135	2.22%	79	82	3.66%
	121	124	2.42%	72	75	4.00%
2	131	139	5.76%	87	93	6.45%
	115	122	5.74%	81	83	2.41%
	127	131	3.05%	84	86	2.33%
	119	126	5.56%	78	83	6.02%
	132	134	1.49%	86	89	3.37%
3	116	122	4.92%	71	78	8.97%
	121	127	4.72%	72	76	5.26%
	114	119	4.20%	81	82	1.22%
	113	115	1.74%	73	79	7.59%
	108	116	6.90%	65	69	5.80%
4	127	134	5.22%	81	87	6.90%
	125	131	4.58%	73	78	6.41%
	120	129	6.98%	78	84	7.14%
	125	133	6.02%	77	84	8.33%
	119	125	4.80%	69	75	8.00%
		MAPE	4.54%		MAPE	5.43%

Based on Table III data, it is found that the implemented blood pressure measurement system has a Mean Absolute Percentage Error of 4.54% for systolic blood pressure and 5.43% for diastolic blood pressure. From the following figure 8 and 9, it is evident that the device has an off-set, which is why all the measurements from the prototype is consistently a little bit lower than the reference device.

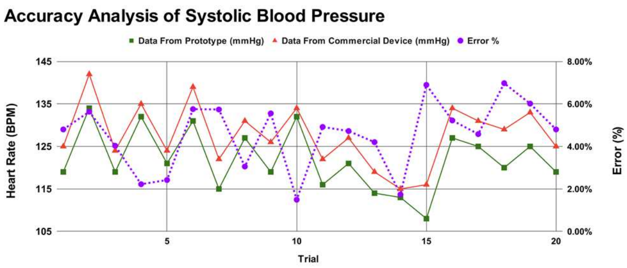

Fig. 8. Error analysis of the prototype and reference device for systolic BP

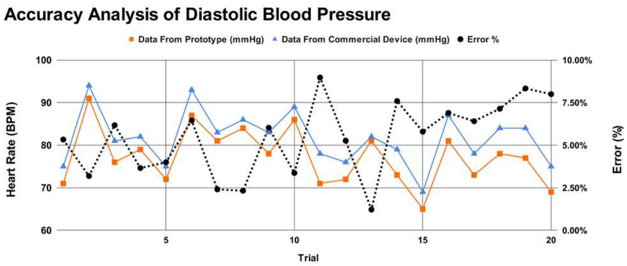

Fig. 9. Error analysis of the prototype and reference device for diastolic BP

D. Development and Accuracy Analysis of Blood Glucose

To develop the NIR-based blood glucose level monitor initially, we have taken a total of 40 readings from 8 different volunteers. The analog values in mV and the original blood glucose level measured by a commercial blood glucose monitoring device in mg/dl are noted, and the readings are tabulated in Table IV. BG is used in the table as the short form of Blood Glucose.

TABLE IV. ANALOG VOLTAGE AND REAL BLOOD GLUCOSE DATA

Sample	Voltage (mV)	BG (mg/dl)	Sample	Voltage (mV)	BG (mg/dl)
1	499	142	21	609	163
2	509	146	22	602	174
3	519	156	23	423	111
4	519	157	24	584	177
5	548	177	25	502	145
6	524	159	26	524	163
7	543	209	27	541	172
8	568	133	28	517	153
9	573	179	29	511	147
10	583	224	30	522	158
11	592	175	31	489	137
12	597	187	32	473	125
13	607	196	33	507	151
14	627	191	34	597	178
15	695	167	35	583	189
16	735	220	36	503	132
17	612	244	37	595	178
18	847	247	38	598	184
19	833	248	39	567	165
20	867	276	40	495	143

Based on the collected data, we have generated a 2nd order polynomial equation. The equation is used to measure the blood glucose approximately, and the analog voltage is used as input, and the output is the blood glucose level in mg/dl. The equation 5 is the generated equation.

$$y = 3 \times 10^{-5}x^2 + 0.2903x - 4.789 \tag{5}$$

After implementing the equation in the system, the system's performance is evaluated for 10 test cases to determine the accuracy, and the data are tabulated in the following Table V.

TABLE V. ERROR ANALYSIS OF BLOOD GLUCOSE SYSTEM

Sample	Invasive Glucose Values (mg/dl)	Non-Invasive Glucose Values (mg/dl)	Error %
1	117	120	2.56%
2	143	141	1.40%
3	166	162	2.41%
4	134	151	12.69%
5	145	139	4.14%
6	120	129	7.50%
7	123	118	4.07%
8	157	142	9.55%
9	193	192	0.52%
10	106	103	2.83%
		MAPE	4.77%

Based on the analysis, it is found that the proposed system has a MAPE of only 4.77%, and it can be utilized as an early indicator of any anomaly in the blood glucose trend. The data is graphically represented in the following figure 10.

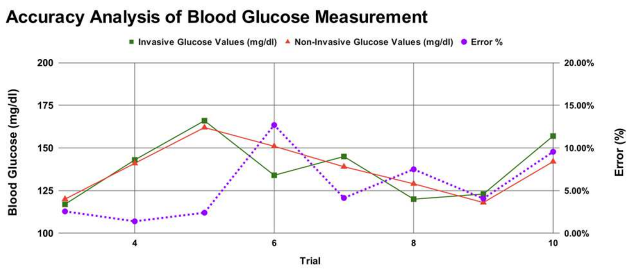

Fig. 10. Error analysis of the proposed Blood Glucose measurement system

E. Fall Detection

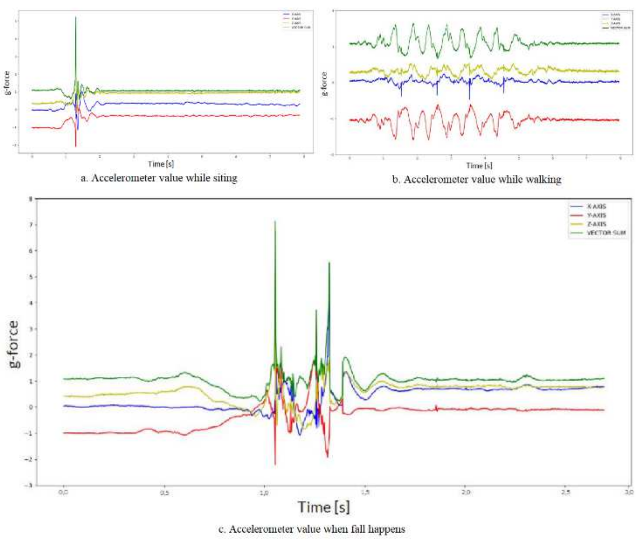

Fig. 11. Values of accelerometer for different actions

For the fall detection, we have used the MPU6050. When a fall occurs, abrupt change happens in the values of the accelerometer in a very short time. The main processing unit looks for these abrupt changes and changes in all axes individually. The change of acceleration while sitting, walking, and falling is depicted in figure 11. In figure 11c, we can see that when the fall occurs, the values of acceleration change drastically within a very short period. These abrupt changes were successfully detected in the processing unit as an event of unwanted fall. From 11a, we can see that though there is an abrupt change in acceleration while sitting, no consecutive acceleration peak was found. Thus, the system mitigates the false detection by only detecting falls when there are multiple peaks.

F. *Fetal Kick Detection*

To detect the fetal kick, we have used the ADXL335 as the sensor responsible for detection, and it is placed on the abdomen of a pregnant woman based on the fetal orientation. In Figure 12, we can see that at 1.2 seconds, there is a spike in the g-force value of ADXL335, but the MPU6050 value is almost stable. At that time, a fetal kick happened, and the volunteer confirmed it. However, we did not do any long-time testing, and multiple positions were not evaluated during this testing phase.

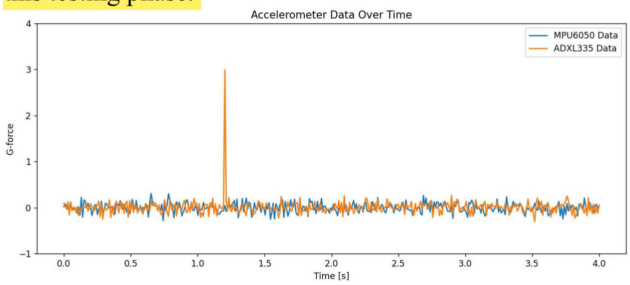

Fig. 12. Value of IMUs when fetal kick occurs

G. *SMS Alert*

The system has a feature that sends SMS when it detects any anomaly. Few of the test cases were emulated, and the received texts are depicted in the following figure 13.

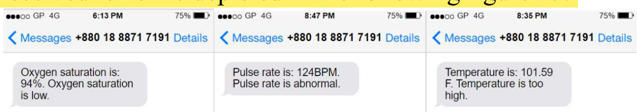

Fig. 13. SMS alert in case of emulated abnormalities

H. *Cost analysis*

TABLE VI. COST ANALYSIS

Component	Cost (in USD)
ESP-32	$5
DS18B20	$2
MAX30100	$3
Blood Pressure Machine	$13
MPU-6050	$2
ADXL335	$8
Buck Converter	$2
Miscellaneous	$5
Total	$40

The total cost for the components to make the prototype of the device comes at only USD 40. Such low cost of this device makes it an affordable and low-cost solution to monitor the health vitals of women with pregnancy.

VI. CONCLUSION AND FUTURE WORK

In summary, our validated maternal health care system, encompassing vital sign monitoring and innovative features like fall detection and fetal movement tracking, exhibit satisfactory performance. Notably, while the fetal movement algorithm demonstrated efficacy in simulated environments, future research should prioritize its validation on pregnant women in real-life scenarios. Further research avenues include refining vital sign algorithms through machine learning, assessing user feedback for system optimization, enhancing security measures for data protection, and collaborating with healthcare professionals to seamlessly integrate the system into diverse maternal care settings, ensuring widespread adoption and improved maternal health outcomes.

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