INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, YEAR, VOL. 69, NO. 1, PP. 25–32
Manuscript received May 17, 2022; revised January, 2023. DOI: 10.24425/ijet.2023.144327

Wearable Biosensor: How to Improve the Efficacy in Data Transmission in Respiratory Monitoring System?

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Abstract—**Respiratory rate measurement is important under different types of health issues. The need for technological developments for measuring respiratory rate has become imperative for healthcare professionals. The paper presents an approach to respiratory monitoring, with the aim to improve the accuracy and efficacy of the data monitored. We use multiple types of sensors on various locations on the body to continuously transmit real-time data, which is processed to calculate the respiration rate. Variations in the respiration rate will help us identify the current health condition of the patient also for diagnosis and further medical treatment. The software tools such as Keil μVision IDE, Mbed Studio IDE, Energia IDE are used to compile and build the system architecture and display information. EasyEDA is used to provide pin map details and complete architecture information.**

Keywords—**data format; microcontrollers; respiration; sensors; time synchronization**

I. INTRODUCTION

REMOTE healthcare monitoring allows people to stay at home instead of going to healthcare facilities like hospitals or nursing homes. Which is a more efficient and cost-effective option than on-site patient care. [1] and [2] have suggested that these are useful diagnostic tools for healthcare professionals, allowing them to monitor vital physiological indications and activities of patients in real-time from a remote location. These systems are integrated with non-invasive and discreet wearable sensors. Hence, wearable sensors play an important part in monitoring systems that have caught the interest of many scientists, entrepreneurs, and tech leaders in the past few years. [3] claimed that developing and implementing new strategies and technologies to provide quality healthcare services at an affordable price to the aging population or people. In areas with limited access to healthcare is very much needed in a country like India. Which ensures maximum convenience, independence, and involvement among the people.

The sensitivity of respiratory rate under health challenges is more reactive when compared to that of most of the other vital signs. The alterations in respiratory rate can cause serious clinical events such as cardiac arrest, which leads to admission to the intensive care unit. To discriminate between stable patients and patients at risk, the respiratory rate will be a better parameter than other vital measurements such as pulse and blood pressure. Using changes in respiratory rate measurements, patients could have been identified as high risk up to 24 hr. before the event with a specificity of 95% [4]. Respiratory failure is difficult to predict and can become life-threatening in a few minutes, but it can also build up gradually. It is frequently the result of a chain of more or less related circumstances. The mortality related to acute respiratory failure is significant, taking into account the fact that unexpected cardiac failure during sleep can often be preceded by, or combined with, events of respiratory failure. It is very essential to understand the physiological functions of the human respiratory system with respect to age, diet, and how it reacts with the host immune system and external pathogens [5]. In recent years, several non-invasive, efficient, and cost-effective respiratory monitoring systems were developed using wearable sensors and actuators to enhance reliability and minimize the patient's discomfort. Bio-signal acquisition using monolithic sensors is becoming more popular for efficient measurements of various physiological data. [4] stated that respiration rate monitoring using non-contact approaches is of high interest because of high accuracy. Respiratory monitoring is very much essential in patient monitoring systems, sleep studies, sports training, or health at work, etc., The various aspects of the system design includes [6], type, size of the sensor and its location, sensing technique, respiration parameter, communication protocol, processing location, power consumption, energy autonomy, sensor validation, processing algorithm, analysis software, and performance evaluation. The design and development of current state-of-the-art solutions in wearable biosensor systems for respiratory monitoring have drawn lots of attention with the recent technological advances in smart textiles, miniature biosensing devices, microelectronics, and wireless technologies, [7]. Wearable sensors can measure both respiration volume and rate simultaneously with high fidelity. [8]. have achieved this by noting the local strain of the abdomen and ribcage during breathing using low-powered piezoresistive sensors A respiratory monitoring system based

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on force-cardiography sensors [9], that measure cardiac-induced vibrations of the chest, and ventricular volume variations [10] ensures 98.9% precision and 100% sensitivity. [11] has used smart sensors of capacitive sensing to monitor respiratory rate which avoids drawbacks of conventional low-sensitive devices available in the market. A wearable sensing system is developed to monitor respiratory using a piezo-resistive Flexi-Force sensor. [12] proposed a system and algorithms which give optimal computation time with minimum error rates of 3.40% in obtaining the respiratory rates. Low-cost, wearable inertial sensors are used for accurate, automatic, and posture-independent breathing rate measurement systems. [13] has mentioned in the article that Optoelectronic plethysmography, PCA-fusion, Bland–Altman analysis are identified as the best methods in terms of correlation, mean absolute errors, spectral analysis. The functioning of the respiratory system under the influence of the presence of toxic chemicals in the air is explored by [14]. The stretchable, wearable strain sensor system is developed for respiration measurements on a real-time basis during walking exercises. Accurate breath counts with high precision by the sensor system suggested [15] using in clinical practice. Contact-based techniques are presented by [16] for measuring respiratory rate according to airflow, air temperature, and air humidity. A contactless camera-based wireless sensor system is developed by [17] for reliable respiration rate measurements. Raw breathing signals can be extracted from the remote video stream using efficient algorithms. Non-invasive methods for respiratory monitoring are in the development phase that measures respiratory depth, rate, and gas exchange [18]. Lungs are the gas-exchange (inhale oxygen and exhale carbon dioxide) organs located in the thorax of a human, [19]. Particle transport and airflow mechanism in the lungs are modeled by [20] with the help of recent advancements in visualization techniques and 3D anatomical models. MEMS-based inertial measurement units are used for the accurate detection of respiratory cycles and their lengths. To measure respiratory patterns and rates, [21] used respiratory motion estimation quantitatively with respect to both magnitude and phase Video frames from the non-contact cameras. This system tracks chest movements by extracting the breathing signal from images using RGB analysis, optical flow, and identifying the possible apneas. [22] has shown in their study for the respiratory range of 6 - 60 breaths/minute (bpm), the measured values are biased by -0.03 ± 1.38 bpm compared to a wearable system where the user is located at a 2m distance from the camera. Ultrasonic sensors can be used for efficient real-time monitoring of breathing activity to detect abnormalities like central apnea, tachypnea by tracking thorax movement. Piezo respiratory belt transducer is used to minimize the power consumption of the respiratory monitoring system with energy-efficient duty cycles and low error rate, [23]. Thermistor-based breathing rate measurement of a patient by [24], the thermistors are placed in a mask where the patient breathes through, and it is easy accessing even the patient is suffering from trauma, strokes, coma, and seizures. [25] mentioned that the development of various sensor technologies made feasible non-invasive wearable devices for monitoring human health and data analysis. IoT-based respiratory monitoring system addresses breathing difficulties and brings them to the notice of doctors on a real-time basis. The availability of low-cost, lightweight, and low-power sensors made wearable devices [26] in developing efficient IoT systems. The IoT-based respiratory monitoring system is developed by [27] where Arduino is used for data collection and processing, wireless modules like Wi-Fi for data transmission over the internet. These systems are very much useful for real-time monitoring as well as data analysis. The recent advances in IoT technologies enabled building E-Health systems with wearable devices to provide more comfort and convenience to patients, [17]. Respiration Rate is a very important parameter to be considered in the human respiratory monitoring system. A low-cost thermistor is used [18] to measure the temperature of respired air. The number of peaks per minute in the resultant voltage signal gives the respiration rate. Wheezing sound while breathing is a symptom of airway obstruction and auscultation approach is the regular way to diagnose it, however, the physician experience is more important to consider. An automatic system [28], [29], for real-time wheeze detection using low-power wireless wearable devices provides quantitative information for clinical diagnosis. Software applications and tools are very useful in collecting respiratory rate values. The performance of software tools like the Medtronics Nellcor tool in measuring continuous respiratory rate is compared by [30] with capnography and it shows a linear correlation with minimal deviation. Respiration rate and volume are measured the [8] simultaneously using a wearable sensor system based on the local strain of the ribcage and abdomen. This system uses low-power piezo-resistive sensors and wireless devices like Bluetooth, capable of monitoring the respiration of patients who have chronic respiratory diseases. [31] has shown that breath rate analysis can also be performed based on thoracic extensions using inertial sensors like accelerometers, gyroscopes. The recent research is focused on wearable devices based on sensor technologies like inductive, humidity, acoustic, resistive, acceleration, pressure, infrared, electromyography, and impedance are used for respiratory monitoring on a continuous basis under various environmental conditions. Non-invasive breathing analysis using machine learning algorithms in detecting breathing patterns are emerging technologies, [32]. Multimodal fusion architecture of a real-time wireless wearable respiratory and activity monitoring system is developed by [33], to monitor breathing patterns. Deep learning, threshold-based algorithms are used in hybrid hierarchical classifiers for more accuracy (97.22%) and less predictive time (0.0094s) of breathing indices.

Even though there are many research work in the respiration monitoring using wearable sensors, the issues in the data transmission and latency caused when there are multiple sensors used in the wearable system needs to be addressed. The paper proposes a comprehensive

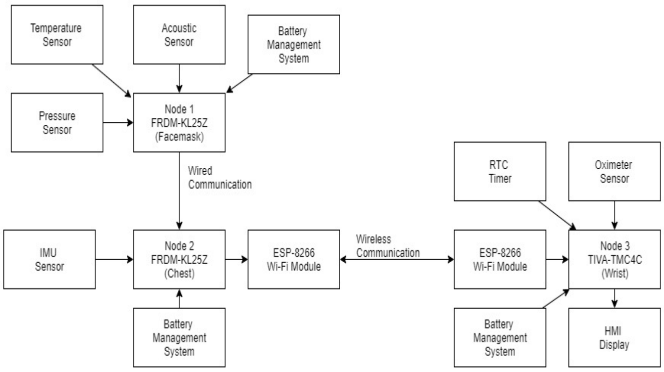


Fig. 1. Proposed Architecture for Comprehensive Respiratory monitoring system.

respiratory monitoring system by designing a wearable system as a Body Area Network, by integrating sensors and microcontrollers to acquire and analyze the data. The data transmission and time synchronization for critical data are discussed. Real-time analysis is made possible by collecting the data in real-time and continuously monitoring respiratory health status over time and providing information to health care professionals.

II. METHODS

The proposed architecture of the system is as shown in Figure 1. The whole system is divided into three nodes that interface one or multiple sensors and send their data to the central node. Different types of sensors were selected based on their position to be placed on the body in a non-invasive manner. Table II depicts the list of the sensors used in the system with the type of interface used for communication and their scope.

The Microcontrollers used are FRM KL25Z is Arm® Cortex®-M0+ processor with Clocks:32 kHz to 40 kHz or 3 MHz to 32 MHz crystal oscillator Operating Characteristics: Voltage range: 1.71 to 3.6 V. And TIVA TM4C 123GH6PM ARM Cortex-M4 core with floating-point CPU speed up to 80 MHz. The microcontrollers were selected based on the computational performance, efficiency, and power requirements for each node. The pre-processing of data for each sensor at its respective node and the post-processing of collected data is done at the central node. The proposed design uses wired communication between Node 1 and Node 2 to transfer the raw sensor data and uses Wi-Fi to transfer the collected data to the central node placed at the wrist. ESP8266 Wi-Fi Module is used for the data transmission. Figure2, Figure3 and Figure4 show the circuit diagram for Node 1, Node 2, and Node 3 respectively. The proposed design is reliable as the entire data is communicated to the cloud server from only Node.3 (central) node.

A. Data Transmission

The data transmission for the whole architecture is as follows:

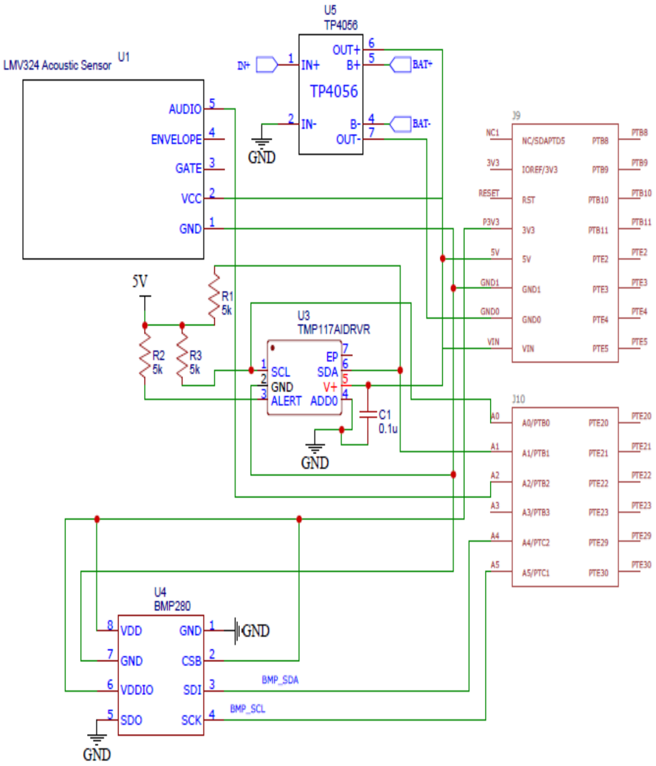


Fig. 2. Circuit diagram for Node 1

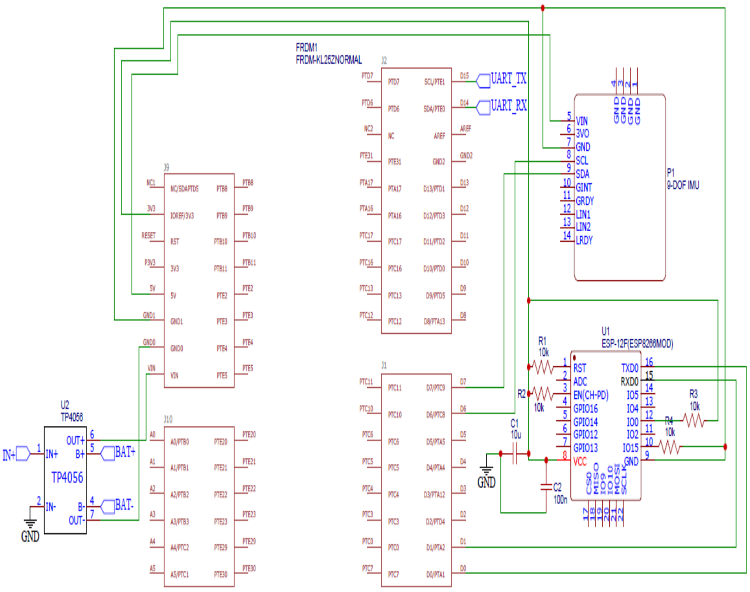


Fig. 3. Circuit diagram for Node 2

Node 1 to Node 2 – Wired Communication (UART)
Node 2 to Node 3 – Wireless Communication (Wi-Fi)

Node 1 interfaces sound, pressure, temperature sensors. The data registers, their data type, and size in bytes are shown in Table III The complete data packets of Pressure, Temperature, and Acoustic sensor format are sent from Node 1 to Node 2 through UART communication. The format of the data frame based on data types and

TABLE I
LIST OF THE SENSORS AND HARDWARE USED IN THE SYSTEM WITH COMMUNICATION PROTOCOL USED AND THEIR SCOPE

Node	MCU	Sensor	Module Name with specifications	Body Location	Interface	Scope
1	KL25Z	Temperature	**TMP117** • Operating temperature range: –55°C to +150°C • Low power consumption Supply range: 1.8 V to 5.5 V •16-bit resolution: 0.0078°C (1 LSB Medical Grade)	Nasal area (Face Mask)	I2C	Detecting breathing instances
		Pressure	**BMP280** •Pressure Range: 300 to 1100 hPa •Accuracy: +/- 1 hPa •Digital Interfaces available: I2C, SPI •Current Consumption: 2.7Ua @ 1Hz sampling rate	Nasal area (Face Mask)	I2C	Detecting breathing instances and recognizing between normal and deep breaths.
		Acoustic	**Sparkfun LMV324** •Output voltage range: 0.01V to 2.69V •Input voltage range: -0.25V to +1.5V •Operating temperature range: -40°C to +125°C •Gain Margin: 17dB •Fully specified at +2.7V and +5V supplies	Neck	ADC	Identify crackles, rhonchus, wheezing sounds, loud snoring. Detect disorders like sleep apnea
2	KL25Z	IMU	**Grove- IMU 9DOF** (lcm20600+AK09918) •Operating voltage: 3.3 to 5 V •Gyroscope Full-Scale Range: ±250 dps, ±500 dps, ±1000 dps, ±2000 dps •Accelerometer Full-Scale Range:±2g, ±4g, ±8g, ±16g	Chest	I2C	Detecting breathing patterns with respect to physical activity
3	TIVA TM4C123GH6PM	Oximeter	**Max30100** •Operating voltage: – 1.8V to 5.5 V •Low-Power Heart Rate Monitor (< 1mW) •Response time: 50 100 µs •-40°C to +85°C Operating Temperature Range	Tip of Finger	I2C	Measuring and analysing blood saturation percentages, Heart rate monitoring

their sizes at Node 1 is shown in Figure6. The data are transmitted by masking all the higher data bytes of sensor data to extract the byte values pertaining to the order of significance. To identify the failure of UART transmission or for debugging purposes, a unique acknowledgment is sent back from Node 2 after all of the bytes for a sensor value are transmitted from Node 1. Failure to receive acknowledgment for a period of time causes the whole set of values to be discarded and the next set of values to start transmitting. This is done to prevent data mismatch at the next nodes.

Node 2 interfaces IMU sensor, as well as collects data received from Node 1. The combined data registers, their data type, and size in bytes are shown in Table IV. The frame format is shown in Figure7. Additionally, time-sync frames are used to synchronize the timestamp on all the sensor values. Data is stored in a byte array at each node for simplicity of transmissions and error checking. This way, the design of the frame primarily depends on the registers used for storing each sensor data, their data type, and corresponding size in bytes. The data received through UART by Node 2 is combined with the data of the IMU sensor interfaced with it, which is sent to Node 3 using ESP8266 Wi-Fi modules. Two ESP8266 modules are interfaced with Node 2 and Node 3 for sending and receiving data, respectively. The Wi-Fi transmission takes through a TCP connection between the two ESP modules.

TABLE II
DATA REGISTERS AT NODE 1

Registers	Data Type	Size in Bytes
RMS_SOUND	$unit16\_t$	2
RMS_TMP	$Float$	2
RMS_PRES32	$Unit32\_t$	4

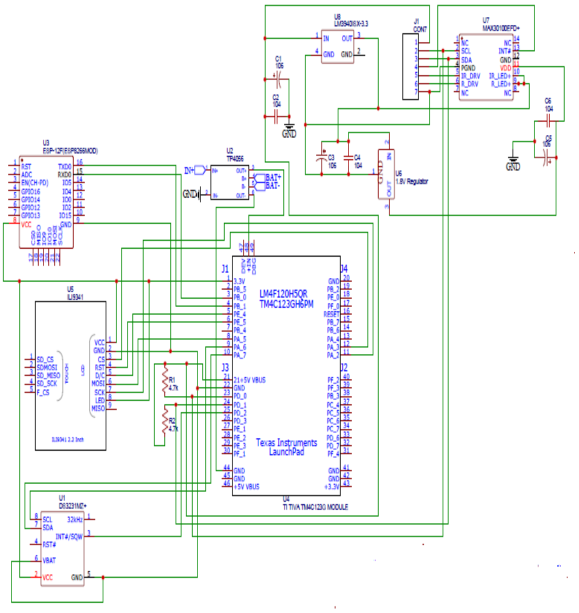


Fig. 4. Circuit diagram for Node 3

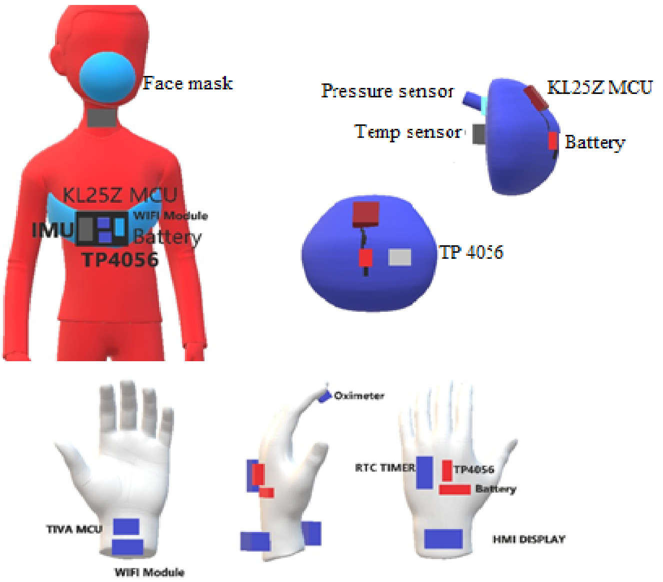
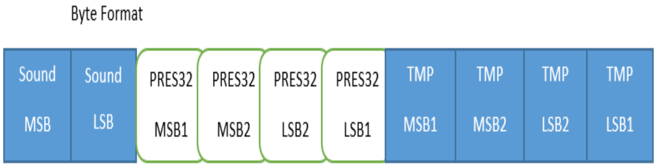


Fig. 5. 3D models of the complete system



Sound	Sound	PRES32	PRES32	PRES32	PRES32	TMP	TMP	TMP	TMP
MSB	LSB	MSB1	MSB2	LSB2	LSB1	MSB1	MSB2	LSB2	LSB1

Fig. 6. Frame format at Node 1

This is done via a series of AT commands which start/stop the connection as well as set the parameters for it. The AT command set is a command language with a series of short text strings, which combine to output complete commands for different operations such as hanging up, dialling, and changing connection parameters for modems. ESP8266 uses its original firmware to process any AT commands that it receives over its Serial UART interface. The biggest advantage of this option is that no specific framework is needed to use the module. A series of commands is simply sent serially to achieve the desired function for networking.

TABLE III
DATA REGISTERS AT NODE 2

Registers	Data Type	Size in Bytes
RMS_ROLL	*Double*	8
RMS_PITCH	*Double*	8
RMS_HEADING	*Double*	8
RMS_SOUND	*unit16_t*	2
RMS_TMP	*Float*	2
RMS_PRES32	*Unit32_t*	4

Data packets are collected at Node 2 and sent to Node 3 through Wi-Fi transmission in the format as given in Figure6 Every microcontroller has its own clock drift and thus the internal timer used at Node 2 MCU may not count at clock ticks the same as with RTC time of Node 3 and thus this would lead to an error. To counter this, time-sync frames are used in the frame format which can align the Timestamp data at regular interval of time.
This timestamp transfers from Node 3 to Node 2 involves:

- Sending a Unique Identifier in the same data frame length
- Identifying the Unique Identifier (AT Node3) and closing the TCP Connections
- Switching the roles played by the nodes (TX and RX)
- Transferring the timestamp to Node 2
- Closing the connections and again switching the roles back to the original

According to the placement of the sensors on the human body as depicted in Table II and the proposed architecture, 3D models are generated for the whole system. These models help to review and analyze the integration of the whole system with the human body. According to the placement of the sensors, the system would primarily be placed on the face mask and neck, chest, and wrist. The models of the same positions are displayed in Figure5

B. Queue Implementation

At Node 3, we have also provided a dynamic queue with a queue lock for controlled access to store multiple sets of data temporarily on Node 3 MCU. Figure8 shows the queue implementation for Node.3. This is done for having future feature implementations that we have felt necessary to improve and provide additional features to this system which is discussed in the Future Scope Section.

Fig. 7. Combined Frame format

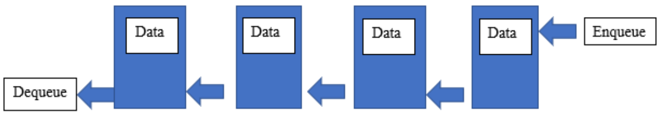
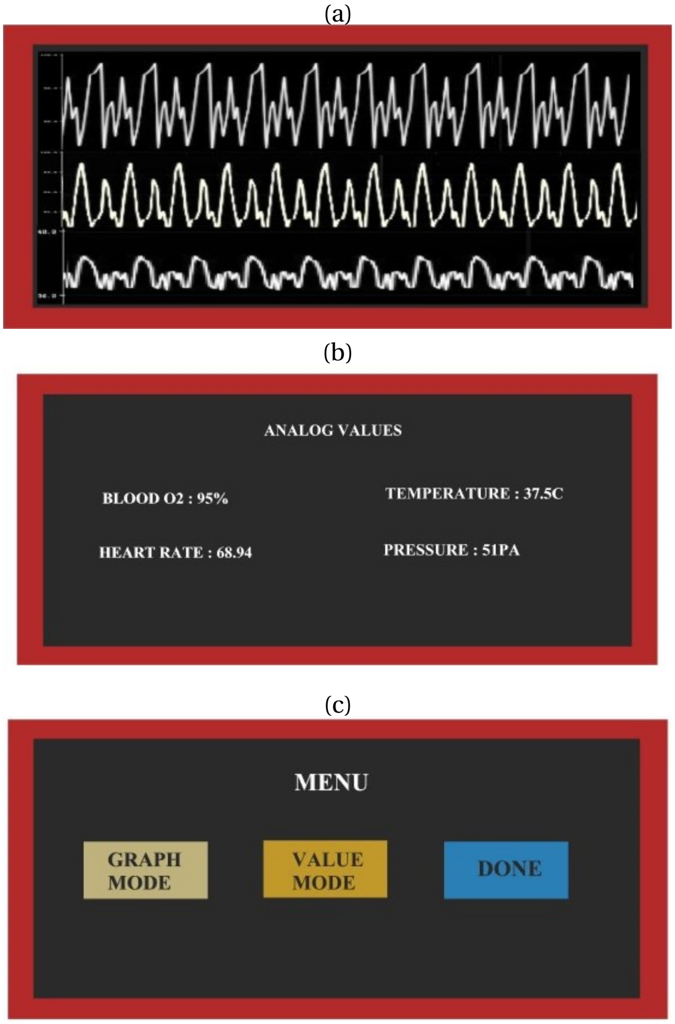


Fig. 8. Queue Implementation of Node 3

III. RESULTS AND DISCUSSION

A sample input data set was generated for sensors interfaced at Node 1. The data values received by the sensors at Node 1 are transmitted to Node 2 in a data frame 2 via UART. As shown in Figure6, the data frame is a byte array of size 10 containing the sensor values received from Node 1. The number of bytes are assigned according to sensor ranges and type of data received from them. The first two bytes for acoustic sensor, next four bytes for pressure sensor, next four bytes for temperature sensor. The data format at Node 2 as given in Figure7 with eight bytes each for roll, pitch and heading. The first ten bytes for each data frame are the same, signifying the data frame received from Node 1. The next twenty-four bytes signify the roll, pitch and heading which are calculated from the data sets of input values of accelerations and magnetic intensities. A sample input data set was generated for IMU sensor interfaced at Node 2. The IMU takes accelerations and magnetic intensities in x, y, z directions as input. The data can be used to measure the angular changes while inhalation and exhalation. At Node 3, sample input data set was generated for Oximeter sensor interfaced. The Oximeter sensor measures blood oxygen percentage and heart rate. Node 3 stores the calculated data from all nodes in the form of datasets indexed by their timestamps. After receiving, preprocessing, transferring and post processing the data from all the sensors in the system, we generate the final set of eight data values at Node 3.


(a)
(b)

ANALOG VALUES

BLOOD O2 : 95%

TEMPERATURE : 37.5C

HEART RATE : 68.94

PRESSURE : 51PA

(c)

Fig. 9. HMI display (a) Sample figure in Graph mode (b) Sample figure in Value mode (c) Sample figure for Menu mode

TABLE IV
EXPECTED VALUES

Parameter to be measured	Expected range
Breath temperature	27.23° C - 27.71° C
Tracheal Breath Sounds	20db - 85db
Tracheal Breath Sounds	28cmH20 – 96cmH20
Roll due to chest wall movement	-10° - +10°
Pitch due to chest wall movement	-10° - +10°
Heading due to chest wall movement	-8° - +8°
Blood oxygen	92% - 100%
Heart Rate	60bps – 100 bps

The HMI display used to show the sensor data on a TFT LCD screen as graphs as well as numeric values. The user can switch between the two modes by using the touch interface. Sample figures for the display are generated to visualize how the information is displayed on the screen. Figure9 features HMI display showing sample output graphs for respiration temperature, blood oxygen and heart rate; the set of output values in numeric mode; A menu screen showing to switch between the two modes as well as for debugging purposes if needed. The Table IV gives the expected range of values for the various physiological parameters.

IV. CONCLUSIONS AND FUTURE SCOPE OF WORK

A system architecture is proposed for the comprehensive respiratory monitoring system. The numerous factors were analysed concerning the analysis of health conditions by using sensors on the human body. For the selection of the hardware several factors like data accuracy, operating ranges, response times are considered as crucial as it holds preference while designing medical systems that function on the human body. The cycle of implementing research observations and designing new features on its basis was essential for the development of this work. Certain limitations would be Memory exhaustion at node 3 may occur if the queue gets full due to not getting de-queued regularly. The source codes developed for each node use different environments and platforms. This is due to the compatible environments for the different microcontrollers present. If the TCP connection between Node 2 and Node 3 gets abruptly disabled, there is no way to update and store the data from Node 1 and Node 2.And when the battery module is near to exhaustion/is exhausted, data corruption might occur due to incomplete or redundant data that needs to be processed. The Future Scope of Work involves information storage at node.3 by using an SD Card for data storage. It also provides additional data capture of all the spo2 data and heart rate data acquired over time till the TCP connection between the nodes is restored. Dependency over Wi-Fi communication can also be eliminated by directly connecting the node 2 and node 3 to cloud for data storage and constant time capture from the cloud. Implementation of application layer protocols like MQTT or HTTP for the wireless communication making it easier to interact with an online database or server. Machine learning and Data Analysis can be implemented via the google firebase real time functionality. And iimproving system efficiency with respect to power consumption by implementing techniques like sleep modes, radio duty cycle.

REFERENCES

[1] Sumit Majumder; Tapas Mondal; M. Jamal Deen, (2017), Wearable Sensors for Remote Health Monitoring', Sensors (Basel), 17(1): 130. https://doi.org/10.3390/s17010130

[2] Andreoni G., Perego P., Standoli C. (2015), 'Wearable monitoring of elderly in an ecologic setting: The SMARTA project.' 2nd International conference on Sensors and Applications, November 2015.

[3] Pantelopoulos A.; Bourbakis N. (2010), 'A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis' IEEE Trans. Syst. Man Cybern. C, 40, 1–12

[4] Al-Khalidi FQ, Saatchi R, Burke D, Elphick H, Tan S.(2010), 'Respiration rate monitoring methods: a review'. Pediatr Pulmonol., 46(6):523-529. https://doi.org/10.1002/ppul.21416. Epub 2011 Jan 31. PMID: 21560260.

[5] Santacroce, L.,Charitos, I.A., Ballini, A., Inchingolo, F., Luperto, P.,De Nitto, E.,Topi, S.,(2020), 'The Human Respiratory System and its Microbiome at a Glimpse'. Biology, 9, 318. https://doi.org/10.3390/biology9100318

[6] Vanegas E, Igual R, Plaza I., (2020), 'Sensing Systems for Respiration Monitoring: A Technical Systematic Review', Sensors. 20(18):5446. https://doi.org/10.3390/s20185446

[7] A. Pantelopoulos and N. G. Bourbakis, (2010), 'A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis,' IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), vol. 40, no. 1, pp. 1-12, https://doi.org/10.1109/TSMCC.2009.2032660

[8] Chu, M., Nguyen, T., Pandey, V. et al. (2019), 'Respiration rate and volume measurements using wearable strain sensors', npj Digital Med 2, 8. https://doi.org/10.1038/s41746-019-0083-3

[9] Majumder, Sumit et al.(2017), 'Wearable Sensors for Remote Health Monitoring.', Sensors (Basel, Switzerland) vol. 17,1 130. https://doi.org/10.3390/s17010130

[10] Andreozzi E, Centracchio J, Punzo V, Esposito D, Polley C, Gargiulo GD, Bifulco P. (2021), 'Respiration Monitoring via Force cardiography Sensors'. Sensors (Basel).21(12):3996. https://doi.org/10.3390/s21123996 PMID: 34207899; PMCID: PMC8228286

[11] Luis, Juan Aponte et al.(2014), 'Design and implementation of a smart sensor for respiratory rate monitoring', Sensors (Basel, Switzerland) vol. 14,2 3019-32. https://doi.org/10.3390/s140203019

[12] Vanegas, Erik, Igual, Raul, Plaza, Inmaculada , (2019), 'Piezoresistive Breathing Sensing System with 3D Printed Wearable Casin', Journal of Sensors, (4):1-19 . https://doi.org/10.1155/2019/2431731https://doi.org/10.1155/2019/2431731

[13] Cesareo, Ambra et al., (2018), 'Assessment of Breathing Parameters Using an Inertial Measurement Unit (IMU)-Based System', Sensors (Basel, Switzerland) vol. 19,1 88. 27 Dec. 2018, https://doi.org/10.3390/s19010088

[14] R.A. Roth, (2010),'Introduction to Respiratory Toxicology, Editor(s): Charlene A. McQueen, Comprehensive Toxicology (Second Edition), Elsevier, Pages 3-12, ISBN 9780080468846, https://doi.org/10.1016/B978-0-08-046884-6.00901-5

[15] Yamamoto A, Nakamoto H, Bessho Y, Watanabe Y, Oki Y, Ono K, Fujimoto Y, Terada T, Ishikawa A.(2019), 'Monitoring respiratory rates with a wearable system using a stretchable strain sensor during moderate exercise', Med Biol Eng Comput.,57(12):2741-2756. https://doi.org/10.1007/s11517-019-02062-2 Epub 2019 Nov 17. PMID: 31734768.

[16] Massaroni C, Nicolò A, Lo Presti D, Sacchetti M, Silvestri S, Schena E.,(2019) 'Contact-Based Methods for Measuring Respiratory Rate'. Sensors (Basel).;19(4):908. https://doi.org/10.3390/s19040908 PMID: 30795595; PMCID: PMC6413190.

[17] Bartula M, Tigges T, Muehlsteff J., (2013), 'Camera-based system for contactless monitoring of respiration'. Annual Int Conf IEEE Eng Med Biol Soc. 2013; 2013:2672-5. https://doi.org/10.1109/EMBC.2013.6610090 PMID: 24110277.

[18] Folke, M., Cernerud, L., Ekström, M. et al. (2003)., 'Critical review of non-invasive respiratory monitoring in medical care'. Med. Biol. Eng. Comput. 41, 377–383. https://doi.org/10.1007/BF02348078

[19] Klocke, Robert A., Burri, Peter H., Heath, Donald Albert, Weibel, Ewald R., Elliott, David H., Cherniack, Neil S., Siebens, Arthur A. and Beers, Michael F. (2020), 'Human respiratory system'. Encyclopedia Britannica, https://www.britannica.com/science/human-respiratory-system. Accessed 14 August 2021.

[20] Islam MS, Paul G, Ong HX, Young PM, Gu YT, Saha SC.(2020), 'A Review of Respiratory Anatomical Development, Air Flow Characterization and Particle Deposition', Int J Environ Res Public Health.;17(2):380. https://doi.org/10.3390/ijerph17020380 PMID: 31935991; PMCID: PMC7014067.

[21] Lehtonen E, Teuho J, Koskinen J, Jafari Tadi M, Klén R, Siekkinen R, Rives Gambin J, Vasankari T, Saraste A.(2021), ' A Respiratory Motion Estimation Method Based on Inertial Measurement Units for Gated Positron Emission Tomography'. Sensors (Basel).,21(12):3983. https://doi.org/10.3390/s21123983 PMID: 34207864; PMCID: PMC8228885.

[22] Romano C, Schena E, Silvestri S, Massaroni C., (2021), 'Non-Contact Respiratory Monitoring Using an RGB Camera for Real-World Applications'. Sensors (Basel),21(15):5126. https://doi.org/10.3390/s21155126 PMID: 34372363; PMCID: PMC8347288.

[23] Ali Al-Naji, Ali J. Al-Askery, Sadik Kamel Gharghan and Javaan Chahl, (2019), 'A System for Monitoring Breathing Activity Using an Ultrasonic Radar Detection with Low Power Consumption', J. Sens. Actuator Netw., 8(2), 32; https://doi.org/10.3390/jsan8020032

[24] Gagandeep kour, Mohammad Rouman, Geetha.M, (2018), 'Respiratory Monitoring System Using Thermistor' International Journal of Pure and Applied Mathematics Vol 119, No. 12, 11567-11575.

[25] Kamišalić A, Fister I, Turkanović M, Karakatič S., (2018), 'Sensors and Functionalities of Non-Invasive Wrist-Wearable Devices: A Review', Sensors. 18(6):1714. https://doi.org/10.3390/s18061714

[26] B Sumathy et al, (2021), 'Wearable noninvasive Health monitoring device for elderly using IoT', IOP Conf. Ser.: Mater. Sci. Eng. 1012 012011 https://doi.org/10.1088/1757-899X/1012/1/012011

[27] P. S. Akram, M. Ramesha., S. A. S. Valiveti, S. Sohail and K. T. S. S. Rao, (2021), 'IoT based Remote Patient Health Monitoring system', 7th International Conference on Advanced Computing and Communication Systems (ICACCS), pp. 1519-1524, https://doi.org/10.1109/ICACCS51430.2021.9441874

[28] Li, Shih-Hong et al.(2017), 'Design of Wearable Breathing Sound Monitoring System for Real-Time Wheeze Detection', Sensors (Basel, Switzerland) vol. 17,1 171, https://doi.org/10.3390/s17010171

[29] Li, Shih-Hong et al.(2017), 'Design of Wearable Breathing Sound Monitoring System for Real-Time Wheeze Detection', Sensors (Basel, Switzerland) vol. 17,1 171, https://doi.org/10.3390/s17010171

[30] Bergese, Sergio D et al. (2017), 'Multicenter Study Validating Accuracy of a Continuous Respiratory Rate Measurement Derived From Pulse Oximetry: A Comparison With Capnography.', Anesthesia and analgesia vol. 124,4 1153-1159. https://doi.org/10.1213/ANE.0000000000001852

[31] G. Karacocuk et al.,(2019), 'Inertial Sensor-Based Respiration Analysis', IEEE Transactions on Instrumentation and Measurement, vol. 68, no. 11, pp. 4268-4275., https://doi.org/10.1109/TIM.2018.2889363

[32] Taisa Daiana da Costa, Maria de Fatima Fernandes Vara, Camila Santos Cristino, Tyene Zoraski Zanella, Guilherme Nunes Nogueira Neto and Percy Nohama, (2019). 'Breathing Monitoring and Pattern Recognition with Wearable Sensors', Wearable Devices - the Big Wave of Innovation, Noushin Nasiri, IntechOpen, https://doi.org/10.5772/intechopen.85460

[33] Qi, Wen, and Andrea Aliverti. (2020), 'A Multimodal Wearable System for Continuous and Real-Time Breathing Pattern Monitoring During Daily Activity', IEEE journal of biomedical and health informatics vol. 24,8 2199-2207. https://doi.org/10.1109/JBHI.2019.2963048