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Cushy and Cheap Smart Health Monitoring System Incorporating a Ventilator

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Abstract

The handiness of mercantile mechanical ventilators is highly limited in low-income countries due to high rate in the price of its affordability. This factor affects the treatment of so many patients suffering from chronic respiratory syndrome. In this research, a low-cost and easy to use pressure ventilator coupled with a remote health monitoring system to assist the doctors check up on the patients is developed. There is need to maximize the availability of the ventilators in low-income countries at an affordable price tag. This system was developed with the aid of an Arduino nano, ESP8266 based NodeMcu microcontroller, high pressure blower, pressure transducers, humidity and temperature sensor. The developed system was evaluated and compared with existing one, using an actively breathing patient simulator as it mimics through a range of respiratory diseases. In the end, we were able to design a low-cost smart health monitoring system that incorporates ventilator and health vitals monitor. Our Design was implemented and verified to be working and equally satisfying all the specified requirements.

Keywords: COVID-19, Internet of Things, Pulse generator, Pulse Width Oximeter, Smart health monitoring systems

INTRODUCTION

An epidemic escalated by coronavirus in the year 2020 was announced firstly to have emanated from Wuhan, China. As the day passes, the virus grows and transmit rapidly from one individual to next worldwide.About 170,000 people lost their lives in the period of April 2020 due to the pandemic, while more than two million people had been infected with the virus (Evans, 2011). Pneumonia of variable asperity happens to be the symptom manifested by patients suffering from the disease triggered by SARS-Cov-2 infection which affects the human lungs and is also referred to as COVID-19 by WorldHealthOrganization.Report states that 61% of patients suffering from COVID-19 would develop critical cases which accounts for more than 85% of all cases (Ranney *et al*, 2020), while there is possibility of recovery for many of COVID-19 patients after treatment (Evans, 2011).

The intubation process of inserting a cannula or tube into a hollow body organ while applying positive air pressure consistently into the patient lungs in order to maintain them at a flattened state is a procedure through which ventilation can be administered to patients. But invasive ventilators have many limitations that make them less desirable. For example, it can easily

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lead to patient infection as it requires a tube to be inserted into their breathing cavity for breaths to be delivered (Wellington, 2021). A great and more effective alternative is a non-invasive ventilator. A non-invasive ventilator does not require any form of tube placed in a patient's throat.

A study titled Internet of things (IoT) Based Health Monitoring System Development and Analysis was proposed by (Mohammad *et al,* 2022), the primary limitation of this system is the cost associated with its construction and implementation. The system has many complex subunits to design and fabricate, reducing its use within a developing country's population (Khan *et al*, 2022). Investigation into Smart Healthcare Monitoring System in an IoT Environment was proposed in Salini *et al*, (2022), The limitation is that the system uses Raspberry Pi as the main processor which is expensive. Real-time artificial intelligence-based health monitoring, diagnosing and environmental control system for COVID-19 patients was developed by Muhammad *et al*, (2022). The aim was to allow doctors and families to track a patient's health outside the hospital using sensors, cloud storage, data transmission, and IoT mobile applications. Limitations point at allowing poorly trained AI system to inject a patient without a doctor's proper review and approval likewise non clarity of the symptoms (Zia Ur Rahman *et al*, 2022). An IoT-Based Smart Health Monitoring System for COVID-19 patients was developed by Vaneeta *et al*, (2022), the major limitation of this system is security, as data spoofing is easy. So, a separate cloud with encryption-based technology could be required to make the whole system highly secure. The data would be encrypted before it is shared with any of the physicians/doctors (Bhardwaj *et al*, 2022).

The design and construction of a simplified, gas-driven, pressure-controlled emergency ventilator was carried out by Szlosarek *et al*, (2021). This describes a simplified device for pressure-controlled ventilation which works without electricity. The system is limited to a fixed ratio between Peak Inspiratory Pressure (PIP) and Positive End Expiratory Pressure (PEEP), and the ventilation frequency depends on two parameters, which need some training (Szlosarek *et al*, 2021). Microcontrollers are electronically programmable chips that aids various automation needs (Okomba *et al*, 2017). Development of a microcontroller-based ventilator system synchronized with pulse oximeter was carried out by Gölcük *et al*, (2016), the limitation of the system is that it uses fuzzy-based controller to control the behavior of the ventilator device.. Design and implementation of a mechanical ventilator for breathing apparatus was carried out by Hidayat *et al*, (2020), the primary limitation of the system developed herein is that it uses a gear configuration that could wear out quickly, limiting its lifespan (Tsuzuki *et al,* 2021).A low cost open-source mechanical ventilator with pulmonary monitoring for COVID-19 patients was developed by Leonardo *et al*, (2020), and not being able to justify PEEP happens to be the short come of the developed mechanical ventilator (Zuppa *et al*, 2020). The design of a Low-Cost Ventilator using Electronic Components was carried out by Bhujade, (2021). The limitation is that its performance is nowhere near that of a standard Ventilator. The Ventilator is only optimized for price at a great expense of performance. Hence, the Ventilator cannot be used in emergency cases (Bhujade, 2021).

Nigerian hospitals are known to be well under-equipped. Many of them 'don't have instruments to capture patient health vitals in real-time (Samanta *et al,* 2022). Development of standard intensive care units in low-income countries have suffered a lot of set-back due to lack of resources, insufficient equipment's, high cost of supply and maintenance of health care system, limited focus, misappropriation of funds, and very poor critical health care systems (Chase *et al*, 2020). This will definitely demand an increase in supply of ventilators (Garmendi *et al*, 2020). High request for ventilator system has propelled effort and ideas towards lessening the scarcity (Iyengar *et al*, 2020). Grooved ventilator producers are applying flexibility in resources availability to maximize manufacturing of the basic needed equipment's. Reproduction of ventilators using existing architectural design is practiced by some companies who are equipped in high experience and skillful personnel that feature in relevance engineering fields existing (Marti *et al*, 2020).

Based on these premises, a ventilator-based smart health monitoring system using a cost-effective approach was constructed to assist patient with the acute pneumatic syndrome breathe through a ventilator while simultaneouslymonitoring their essential health vitals remotely from any location. The developed system integrates the function of both the ventilator and patient health monitor in its design. This device can be powered using batteries or mains supply, this implies that they can be used during power outages. Due to the compact size nature of the developed system, it could be easily accessible and used in ambulances and private vehicles.

METHODOLOGY

The design and implementation of a Low-Cost portable mechanical ventilator which is Arduino based connected to an actuator for operation was carried out by Bhujade, (2021). This work stands as a motivation to the developed system which is an upgrade having both the ventilator and remote smart health monitoring unit integrated. To achieve this aim, a design of the developed system was carried out as shown in figure 1 and 2, portraying the system block diagram and system flow. This process is followed by the hardware implementation with steps shown by the circuit diagram in figure 3.

To enforce accurate implementation of the breathing cycle of a patient in this study, there is need to abide by the following requirements. The Ventilator must:

i. Produce within the range of 300ml to 500ml in volume of air per breathing cycle.
ii. Ensure that the positive end expiratory pressure (PEEP) is maintained at a range of 5cm H2O and 25cm H2O. PEEP is recognized as the pressure above atmospheric pressure which is found in the lungs
iii. Keep the peak pressure at range starting from 18cm H2O to 25cm H2O.
iv. Ensure the breathing cycle is maintained at 15 respirations per minute.
v. Separate the cycle into phases of inspiration, pause, and expiration.

The health monitoring subsystem must:

i. Measure the patient's health vitals in real-time.
ii. Display the vitals measured on a screen for personnel to see and monitor.
iii. Send the data it collects over a network to an IoT cloud so that it can be monitored remotely.

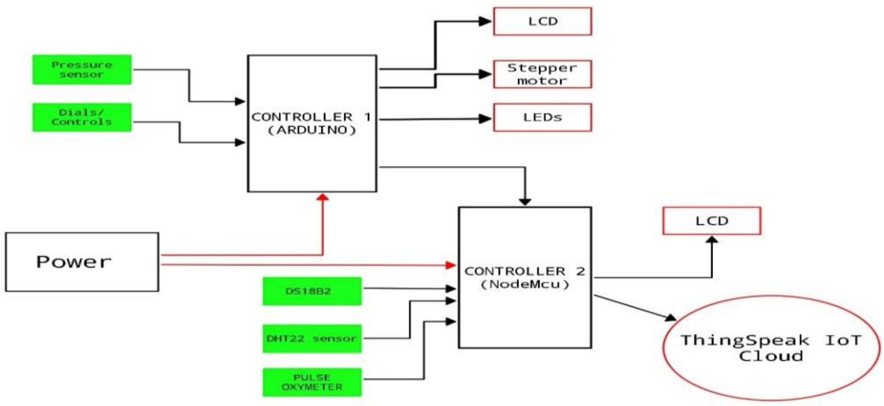

Figure 1: Block Diagram of the smart ventilator

The designed system must fulfil all these requirements while keeping costs as low as possibleusing standard commercial or off-the-shelf components.A manual respirator is part of the ventilator and a device that will compress it through a breathing cycle. The mechanism of this compression is through an electrical motor which operates a lever through a four-bar link mechanism.Sensors such as pressure and flow sensors were used to monitor the operation of the ventilator subsystem.The system contains two controllers (Arduino Nano and a NodeMcu development kit), one for each subsystem. The NodeMcu is based on an ESP32 module. It has the capacity to send information to an IoT server through the internet.Accidents were avoided by employing two sensors to pass feedback signals to the machine.Installation of a flowmeter is applied between the face mask and silicone bag of the tube.The air volume passed through a patient's lungs can be calculated by mathematically integrating the flow and modifications can applied to the cycle in order to maintain adequate volume ranges.To maintain the pressure values not below the PEEP and not above the set maximum threshold, a pressure sensor is introduced for feedback and control assistance.Having a conscious patient use an automatic respirator may not be a good practice. This is because their diaphragm contractions and reflexes in breathing will not synchronize with the programmed breathing cycle.To avoid complications, a conscious patient or patient with reflexes in breathing may need to be fully sedated.

The system will connect to the Internet through the NodeMcu. The NodeMcu module will connect to the IoT server through a Wi-Fi that will be provided. All the ' 'patient's information gathered by the device will be sent to the cloud for visualization and remote monitoring.The Arduino Nano is used to control the operations of the ventilator subsystem and provide information it gathers from sensors to the employed ESP32-based NodeMcuwhich acts as a modem with the aid of its dual mode Bluetooth and Wi-Fi features so that it can transfer the acquired information to the IoT cloud. Voltage regulator was used to regulate the amount of current reaching the board. The developed system make use of an L7812 voltage regulator which have a fixed output voltage of 12 volts and a three terminal positive regulator. Local regulation of voltage are made possible by the fixed regulator, it also made available thermal shutdown control, and internal current limiting. A maximum of 1.5 amp of current is expected output of the voltage regulator.

An AMS5915 pressure sensor was used to measure the patient's airway pressure when connected to the Ventilator. The AMS5915 is a batch series of high precision digital pressure sensors used in ventilators and are suitable for 3.3 volts controllers. A wide temperature range of calibration and compensation starting from 25 degrees to 85degree centigrade was made on pressure sensor, this assist in giving a low overall error in the system. AMS5915 series of sensors are made available for different categories of pressure and set ranges of pressure from -2.5mbar to 2.5mbar up to 16bar. An HD44780 LCD which is a 16x2 LCD Module was used to display information about the health vitals as measured by the system sensors. This device is applied due to its availability, easy to use, reduced cost, easy to program, and academic impact.

A DS18B20 temperature sensor was used to obtain the temperature of the patient. This device is a 1 wire digital temperature monitoring sensor developed by Maxi IC. It provides details of the patient's temperature with degree in Celsius report from precision level of 9 to 12 bit. The internal architecture of each sensor portrays a unique 64bit batch serial numberattached to it which permits multiple number of sensors to access one data bus. MAX30100 sensor module was used to gather information on the oxygen level of the blood and the patient's heart rate. This device has a heart rate oximeter sensor module and a pulse oximeter. This quality makes it very essential in the developed system. This device operates by means of shining a cold light through the fingers which provides a channel for reading the light going through the finger in order to determine the oxygen level in the blood.

The ThingSpeak cloud platform was used for analyzing the IoT services due to its ability to permit aggregation, visualization, and live data streams analysis in the cloud. Arduino IDE was used to code the microcontroller, the codes were written and uploaded to a workspace in real time. Fritzing Cad software was used to build an online prototype of the system, it enables connections between the components and the PCB, and also permits the generation of a PCB layout of the system design.

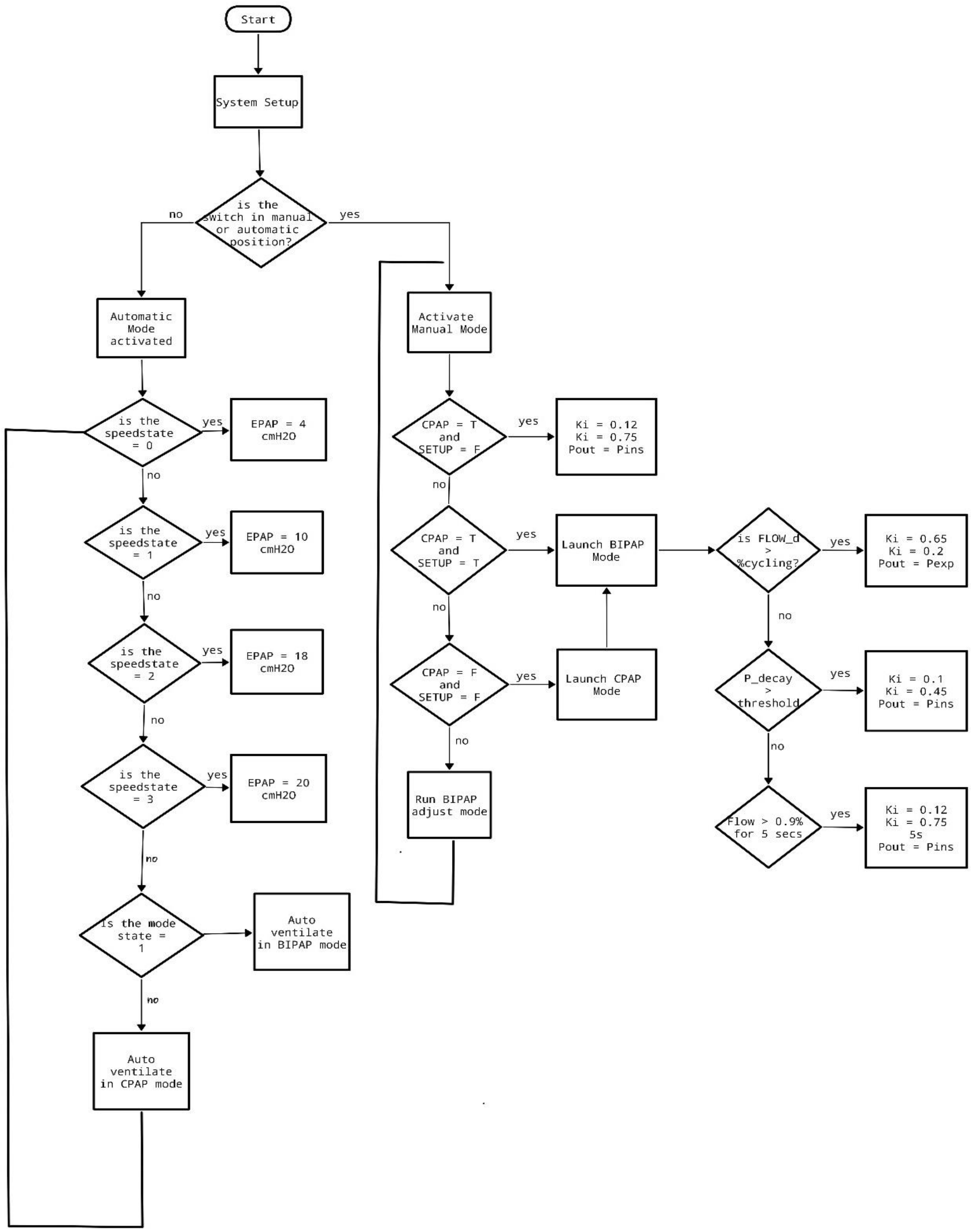

Figure 2: Flow Chart Diagram of the Ventilator System

A general description of the developed smart ventilator algorithmis presented in Figure 2.When the system is turned on, it automatically connects with available wi-fi, initializes vital sensors and boots to a user set up mode.Inspiratory and expiratory pressure, coupled with flow percentage for cycling are the parameter values portrayed at the front panel of the developed system.Each of these values can be modified by the user during ventilation.The pressure transducers are passed through a low pass filter in order to limit noise and they also measures the nasal pressure.High pass filter is applied to the flow signal in order to remove constant flow components that correspond to air flow, this makes the flow signal to correspond with the patients breathing flow.The blower generates expiratory pressure when driven by a detection of pressure biggerthan the set threshold. When the nasal pressure exhibits a negative deflection and it is bigger than the set threshold, the status of the ventilator changes to inspiration mode.This mode changes back to expiratory when there is decrease in inspiratory flow down to a value that corresponds to cycling of maximum inspiration flow percentage.In a situation the system where no new inspiration is detected after five seconds of the previous inspiration, a backup inspiration is triggered. The developed system provides a portal to the webserver through a unique IP address enabling patient caregiver to access the health status of this patient remotely. Figure 3 shows the circuit diagram of the system and its implementation briefly discussed.

The first step taken in the prototyping stage was implementing the circuit diagram of the developed system on an electronic breadboard. This enables us to test out the idea of creating a model that leads to development of other forms. This provides an avenue for building and testing the prototype with given parameters and components before implementing by soldering on a Veroboard [23]. Basic components used in the building of this system include Arduino nano IC, MC78L08CP voltage regulator, XGZP6847 pressure sensors, resistors, capacitors, LCD 2x16 display, pressure triggers, and flow control devices. The Arduino Nano chip has 30 pins, pins 5,6,7, and 8 were connected to pins 11, 12, 13, and 14 of the LCD 2x16 display. The ground pin of the Arduino pin4 (GND) is connects to pi 1 and 5 of the LCD for stable powering. Pin 11 connects to the LED indicator through a 1k ohm resistor. Pin 12 is connected to pin 2 of a flow out control device through a 10k ohm resistor connected parallel to a 2-microfarad capacitor. Pin 13 connects to pin 2 of the air blowing control unit through a 10k ohm resistor connected parallel to a 2-microfarad capacitor.

Pin 15 of the Arduino was connected to pin 4 of the LCD display, while pin 14 was connected to pin 6 of the LCD. A step pressure switch is connected to pin 9 of the Arduino through a 1k ohm resistor, the switch triggers pin 2 and 3 of the LCD through a grounded 10k ohm resistor. Pin 20 is connected to pin 5 of the first XGZP6847 pressure sensor device and pin 1 of a pressure out flow control unit, while pin 19 is connected pin 5 of the second XGZP6847 pressure sensor device. Pins 30 and 29 of the Arduino are connected to pin 1 for 5 volts, and pin 2 for ground. The continuous positive airway pressure (CPAP) or biphasic positive airway pressure (BIPAP) switch was connected to pin 27 of the Arduino chip. The pressure level when breathing in which is a factor of the inspiratory positive airway pressure (IPAP) is activated through pin 22 of the Arduino, while the pressure level when breathing out which is a factor of the expiratory positive airway pressure (EPAP) is activated through pin 21 of the Arduino.

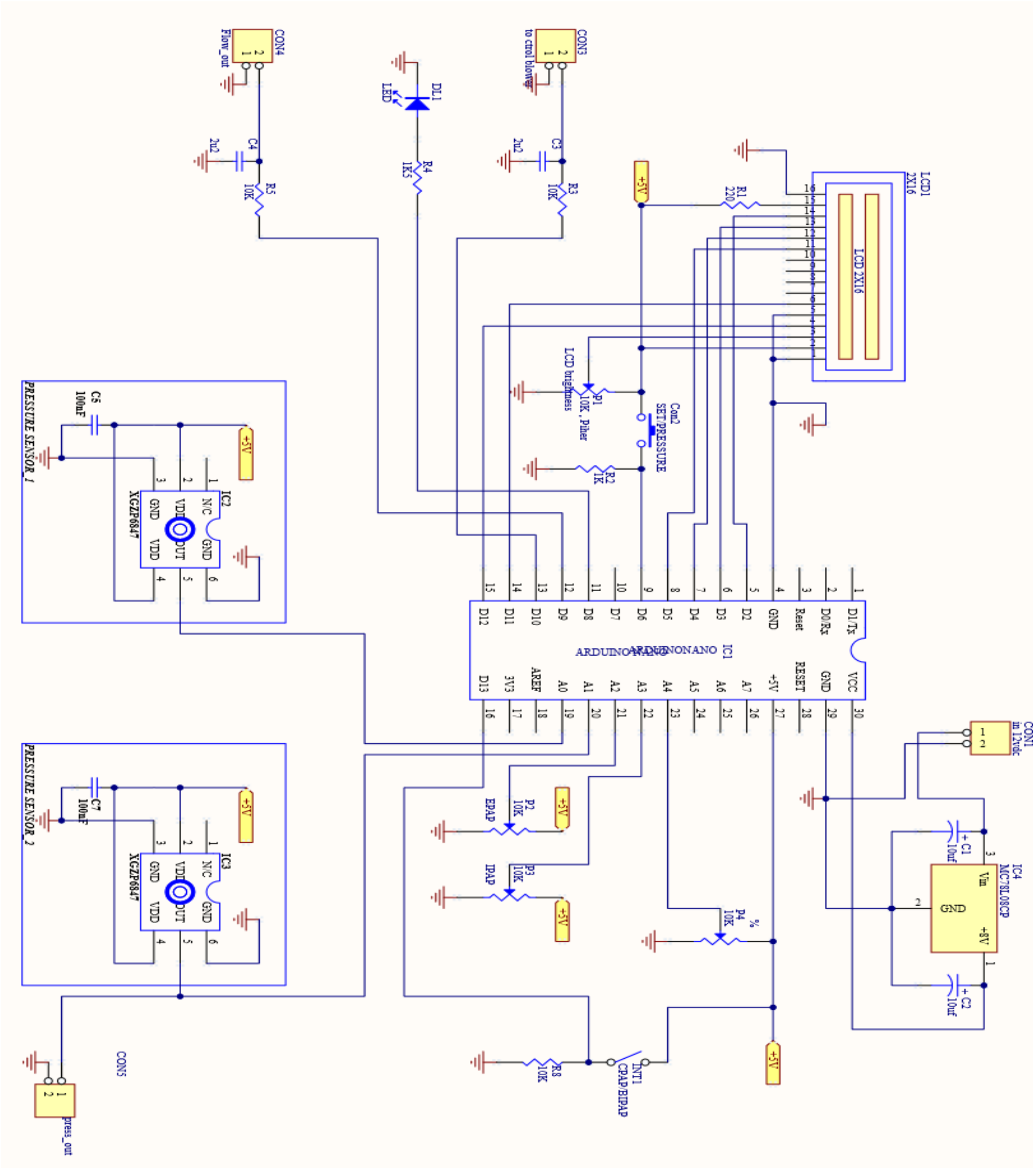

Fig 3: Circuit Diagram of the Developed Ventilator and Health Monitoring

RESULTS AND DISCUSSION

In order to confirm proper functionality of the implemented system, the software and hardware sections were subjected to a bench test. To test the system,a report from two different research papers was used. This was because of no access to an actual ventilator due to its scarcity in Nigerian hospitals. This research paper tested their prototype mechanical ventilator and compared it with two different hospital ventilators used in hospitals. The developed system was evaluated using the aid of a bench test with an active patient simulator that models the mechanics in the respiration of patients with various categories of restrictive diseases.

The pleural pressures simulated in the workbench test is shown in figure 4. The pressure is introduced to passive lung model in order to implement active patient model. In the bench test, position 1 to 4 specifies mild, while 5 to 8 is obstructive, and 9 to 16 is restrictive and obstructive restrictive. Two breathing frequencies of 15 and 20 breaths per minutes were combined with three negative peak pressure amplitude of -6, -9, and -12 cmH_2O to actualize this test.

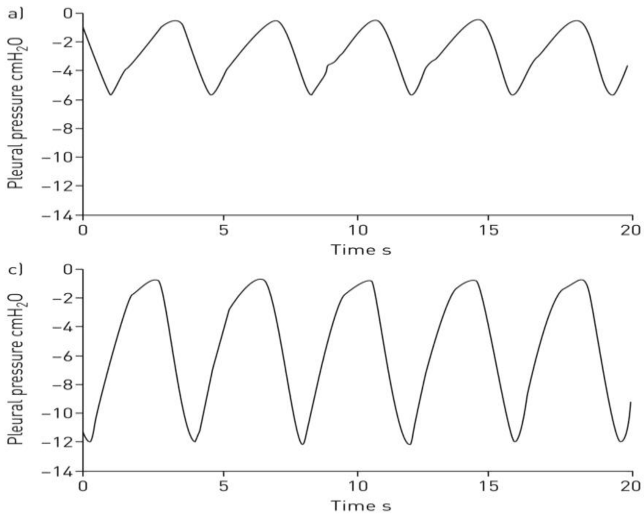

Figure 4: Simulated pleural pressures in the bench test (Garmendia O. *et al*, 2020**)**

The ventilator was tested with four respiratory variable resistance compliance systems while it was mimicking respiratory attributes of patient with mild disease, patient with obstructive flow, restrictive or reduced compliance patient and patient with both obstructive and restrictive challenges. A bench test recording simulating a mild disease patient while considering the nasal pressure and breathing flow signal is shown in figure 5. The developed system replicates the pressure and flow waveforms as seen in conventional hospital ventilator.

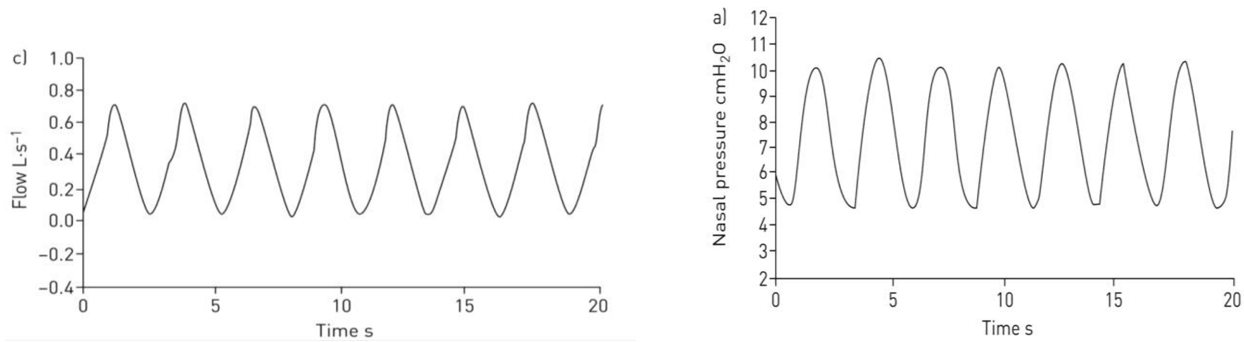

Figure 5: Nasal pressure and Breathing flow signals for mild disease patient

(Garmendia O. *et al*, 2020**)**

The oxygen saturation level is at 96.8±0.9% when aided with a commercial ventilator and 96.8±1.0% when assisted with the developed prototype.When volunteers are subjected to respiratory loading, an average discomfort score of 5.45±1.68 was realized which is reduced significantly to 2.83±1.66 when the developed system ventilator is used to aid the loaded volunteer breathing. It was observed that relief in breathing challenges is approximately the same when compared to 2.80±1.48 score realized using commercial ventilators.

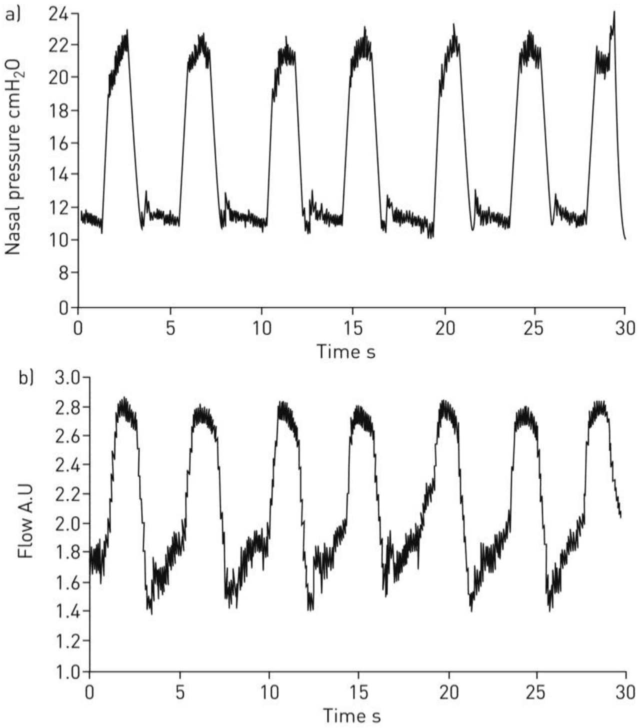

Figure 6: Nasal pressure and flow signals at High NIV (Garmendia O. *et al*, 2020**)**

'Applying the developed system ventilator on a loaded breathing volunteer when set at high values of noninvasive inspiratory and expiratory pressures will illustrate nasal pressure and flow signals as shown in figure 6. Observations from the waveform reflects that the developed ventilator exhibits the breathing pattern of the volunteer, this signifies the absence of unnecessary triggering of the breathing cycle.Figure 7 shows the prototype of the developed system.

Figure7: The system prototyping and assembly process

The existing commercial ventilator portrays pressure waveform close to a square wave signal while the waveform of the developed system changed between inspiration and expiration gradually, and have limited disconnection. There is a sudden increase in the inspiration flow that is induced by existing commercial ventilator at the beginning of inspiration, while the developed system induces flows that increase progressively. Positive results were achieved with the developed system while testing healthy volunteers with resistive and restrictive loads. This depicts the feasibility of the system when applied to humans. Comparing the developed machine base breathing process with the non-machine process, it was observed that the developed system shows no decrease in oxygen saturation throughout the entire test which is required for healthy patients. The developed system is cost effective and provides avenue to monitor patients' health remotely compared to existing systems.

CONCLUSION

Due to the rapid spread of the corona virus (COVID 19) disease in the year 2020, high demand of ventilators became a common trend. Most companies into ventilator manufacturing have to reallocate resources to maximize equipment production and also made available their production design freely to assist engineers venturing into ventilator production. Technology trends focused on assisting through development of low-cost ventilators suitable for low-income countries. A low cost easy to use ventilator and health monitoring system have been developed. The developed system will heavily assist respiratory challenged patients in Nigeria and many other low-income countries in Africa and the world at large. We were able to meet the objectives of designing a smart health system that incorporates a ventilator and health monitor for critically ill over COVID19 patients; Implementing the designed system using readily-available components. Validating the developed system and ensuring it meets its functional requirements.

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