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Design and Implementation of a Portable Ventilator with Variable Breath per Minute (BPM)

Mathew Oluwole Arowolo[1], Cyril Omeiza Ohiani-Greg[1], Ademilua Busayo Ademola[1]
[1]Department of Mechatronics Engineering,
Federal University, Oye,
Ekiti State,
Nigeria.

Email: arowolo.oluwole@fuoye.edu.ng

Abstract

The Covid-19 pandemic underscored the critical role of ventilators in society, prompting attention to the shortage and cost of medical ventilators. This study focuses on the development of a portable ventilator designed for use in resource-limited settings, addressing the need for a small, lightweight mechanical ventilator. The device, controlled by an Arduino microcontroller, features adjustable ventilation modes and monitoring capabilities for vital signs. Utilizing a cam arm mechanism and a touch screen LED display, the ventilator aims to provide reliable and cost-effective ventilation. Evaluation includes performance, usability, and safety assessments. The device, weighing 11 lbs. and measuring 6.6 x 11.4 x 9.4 inches, contributes to accessible and portable ventilators for emergency situations, benefiting rural communities with vulnerable populations and limited hospital ventilators. The ventilator system, powered by an internal battery lasting up to three hours, offers hot-swappable detachable and external batteries for extended ventilation.

Keywords: Portable ventilator, Mechanical ventilation, Heart pulse oximeter sensor, Arduino microcontroller, plywood.

INTRODUCTION

Respiratory diseases such as COVID-19 and respiratory failure caused by injuries made a big impact on public health problems in both developed and less developed countries (Liaqat et al, 2022). These types of diseases are primarily caused by air pollution, smoking, and burning of biomass for fuel, all of which are increasing in developing countries (Jadav *et al*, 2021). Ventilators are medical machines that help patients by mechanically assisting their oxygen level, and exhale, allowing the exchange of oxygen and carbon dioxide to be done within the lungs (Andres et al., 2023). This process is known as artificial respiration (Branson *et al*., 2012). Also, the covid-19 which is spread by air medium or community transmission is very dangerous for human beings. Patients who suffer from lung diseases may experience respiratory failure under various circumstances, and mechanical ventilation support becomes very important for their survival (Pearce, 2020). Adnan, (2022) 'Evidence-Based Mechanical Ventilatory Strategies in ARDS' Journal of clinical medicine, 11(2), 319, stated that, Acute respiratory distress syndrome (ARDS) remains one of the leading causes of morbidity and mortality in critically ill patients despite advancements in the field. Mechanical ventilator strategies are a vital component of ARDS management to prevent secondary lung injury and improve patient outcomes (L'Her & Roy, 2011). While modern hospital ventilators are highly reliable and technologically advanced, their high acquisition costs make them prohibitively expensive for resource-poor and developing countries (Hussain *et al*., 2018).

Made-in-china, a Chinese website, sells the transport emergency ventilator VG70 with Aeonmed for a high price ranging from 8,500-12,000 US dollars. Transport ventilators, also known as portable ventilators, are mechanical ventilation devices designed specifically for emergency or transport scenarios. They are easily moveable therefore portable and serves the same purpose as the hospital ventilator (D'Orsi *et al*., 2017).

Our Research involved the use of an Arduino microcontroller for the control of the ventilator system. The microcontroller was used to turn on the motor driver and rotate the cam mechanism to compress the BVM bag and deliver air to the patient's lungs until the desired pressure level is reached. This is unique and different from existing ones because its pure automatic diver sharply from the manual type (Güler & Ata, 2010).

To ensure patient safety, the ventilator will contain features that monitor the patient's blood oxygen level and lung strain during exhalation, preventing any potential issues related to gas tension. The primary objective of this work is to develop a cost-effective and portable ventilator that can be utilized during times of pandemics and other emergencies (Ahmad, 2019).

METHODOLOGY

Operation Methodology

This research project made both the use of volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV) for the controlling of air into the lungs (Bucher *et al*., 2022). In volume-controlled ventilation, the ventilator will deliver a fixed amount of air to the lungs of the patient, regardless of the pressure required while in pressure-controlled ventilation (PCV), the ventilator delivers air to the lungs of the patient until a certain pressure is reached, regardless of the amount required. Each mode has its advantages and disadvantages, depending on the patient's lung characteristics and respiratory mechanics (Levitan, 2004).

The ventilator system was controlled using Arduino microcontroller (Steuerwald *et al*.,2016). The study also contain features that monitor the patient's blood oxygen level and lung strain during exhalation, to prevent any potential issues related to gas tension. We developed a cost-effective and portable ventilator that can be used during times of pandemics (covid-19) and other emergencies (Ranney & Griffeth, 2020).

Our ventilator design uses a bag-valve-mask (BVM), which is a plastic bag that can be squeezed either manually or automatically to deliver air to the lungs of the patient, then a mechanism that will press the BVM automatically and repeatedly, such as a cam mechanism, solenoid valve, or pneumatic cylinder (Otten *et al*., 2018), but in this our project we used a cam mechanism Sall *et al*., 2018). A control panel that adjust the ventilation parameters, such as tidal volume, respiratory rate, pressure relief valve, and alarms, a battery pack that can provide power to the device for a certain period, an LED display screen used to display the important signs recorded from the patient, such as oxygen saturation, heartbeat rate, and blood pressure (Kim et al., 2018).

The design involved integrating components such as microcontrollers (Arduino) or PLCs, sensors for pressure, airflow, and oxygen levels, actuators for adjusting parameters, LCD screen, keypad, alarm system, power management module, and an enclosure (Cierniak *et al.*, 2018). A control algorithm was developed to calculate parameters for BPM, inspiration, expiration, and tidal volume (Delorenzo et al., 2018). The user interface allows input and adjustment of settings. Proper safety mechanisms and regulatory compliance are considered (Becker & Langhan, 2020).

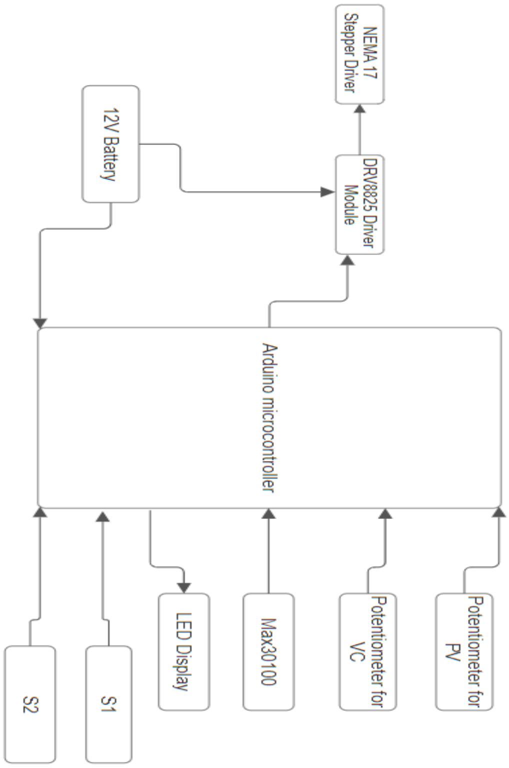

Figure 1: Block Design

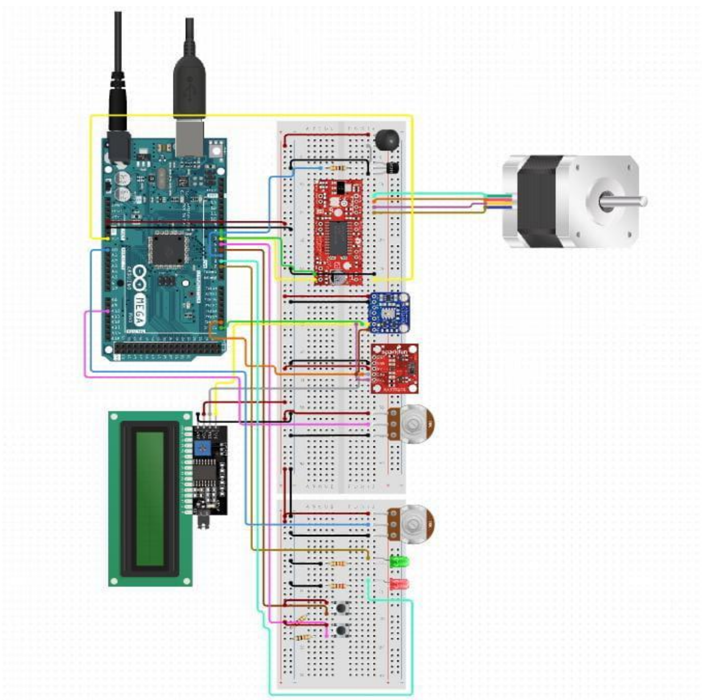

Figure 2: Circuit Design

The ventilator had the following capabilities:

- ❖ Adjustable tidal volume up to 750 ml, set by a knob that changes the cam profile.
- ❖ Adjustable breaths per minute (BPM) up to 30, set by a knob that changes the motor speed.
- ❖ Assist-control mode that detects spontaneous inhalation and triggers a breath.
- ❖ Pressure sensor that monitors the airway pressure and activates an alarm if it exceeds a threshold.
- ❖ Oximeter that measures the blood oxygen saturation and pulse rate of the patient and displays them on an LCD screen

The prototype was built with plywood, measuring 40 x 30 x 20 cm and weighing 9 lbs. (4.1 kg). It was powered by a 14.8 VDC battery and had a prototyping cost of $200
The prototype was tested on a lung simulator and showed satisfactory performance in delivering the desired tidal volume and BPM. The assist-control mode was able to detect inhalation attempts and synchronize with the patient's breathing pattern. The pressure sensor and oximeter were able to provide accurate readings of the airway pressure and blood oxygen saturation, respectively (Costello *et al*., 2017).

Materials and Components Used

- ❖ Arduino Mega Microcontroller - (328P)
- ❖ Servo Motor - AC Servo Motor
- ❖ BVM Bag - Self inflating BVM Bag
- ❖ Led (Liquid Crystal Display)
- ❖ Max30100 (Oximeter)
- ❖ Potentiometer - Multi – Turn Pot Type
- ❖ Power Pack - Linear power supplies Type

Arduino Mega Microcontroller
The Arduino Mega board is a microcontroller board that offers a wide range of functionalities. It allows for programming to carry out tasks and facilitates communication, with sensors, actuators and other external devices connected to it. In this project we will utilize the Arduino Mega board to regulate the functioning of the ventilator. With a total of 54 input/output pins 16 analog inputs, 4 UARTs (hardware ports) a 16 MHz crystal oscillator, USB connectivity, a power jack, an ICSP header and a reset button the Arduino Mega board provides us with all the necessary components. Programming can be done using Arduino IDE in conjunction, with C++ language.
To enable the operation of the ventilator system the Arduino Mega board is interconnected with crucial components including the motor driver pressure sensor, control panel and battery pack.

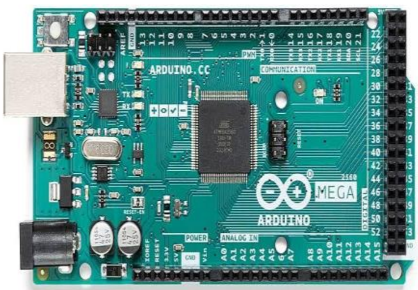

Figure 3: Arduino Mega Microcontroller

Servo Motor

A servo motor is a type of motor that can rotate with great accuracy. It is used to control position, speed and acceleration of a mechanical system. In this study, the motor is used to compress and decompress the BVM bag automatically and repeatedly, according to the desired ventilation mode and parameters.

Figure 4: Arduino Mega Microcontroller

The input signal from Arduino is a PWM (pulse width modulation) signal that defines the duty cycle of the output signal. The duty cycle is the percentage of the time that the output signal is high to the total time of one cycle. The duty cycle affects the position, speed, and direction of the motor. For instance, a 50% duty cycle means that the output signal is high for half of the time and low for half of the time, which makes the motor stop at the middle position. A higher duty cycle means that the output signal is high for more time than low, which makes the motor rotate clockwise. A lower duty cycle means that the output signal is low for more time than high, which makes the motor rotate counterclockwise.

In this project, the motor is used to squeeze a bag that gives air to a patient's lungs. We change the signal to make the bag squeeze the right amount, helping the patient breathe.

BVM Bag

A BVM bag is a vital part of this project, as it helps patients breathe artificially. This bag can be squeezed by hand to send air or oxygen into the patient's lungs through a mask or tube. It might also come with extra parts like a bag to store oxygen and a valve to control the oxygen and pressure levels. In emergencies like heart issues or breathing problems, it's a lifesaver until more advanced help arrives.

Figure 5: BVM Bag

In this project, the ventilator uses the BVM bag as the main piece. It's connected to a mechanism that squeezes and releases the bag at the right speed and amount. It's also linked to an oxygen supply, a bag for extra oxygen, a pressure valve, and a sensor. The machine can work in two ways: one keeps the pressure steady, and the other keeps the air amount steady, depending on what the patient needs. It can even switch between these modes automatically. The BVM bag is crucial because it helps the patient to breathe. The airflow can be adjusted by the controls on the machine.

LED (Liquid Emitting Diode)
A LED display is a device that shows information in the form of light-emitting diodes (LEDs) that can be turned on or off to create patterns of pixels. A LED display is useful for your project, as it allows you to display the parameters and the status of your portable ventilator, such as tidal volume, respiratory rate, inspiratory pressure, inspiratory time, oxygen concentration, battery level, alarms, etc.

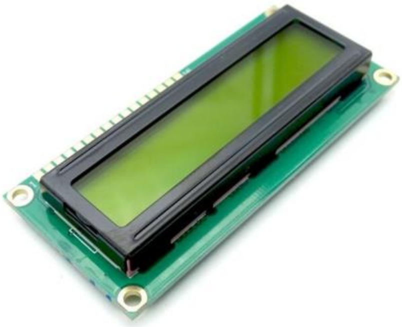

Figure 6: LED Display

A LED display can also show graphical representations of the pressure, flow, and volume waveforms of the ventilation cycle, which can help you monitor the patient's condition and the ventilator's performance. A LED display can be designed to be clear, bright, and easy to read, even in low-light or outdoor environments. A LED display can also be energy-efficient and durable, which are important features for a portable device. A LED display is a key component of your project, as it provides you with visual feedback and guidance on how to use your portable ventilator effectively and safely.

MAX30100 (Oximeter)
The device has two LEDs, one emitting red light, another emitting infrared light. For pulse rate, only infrared light is needed. Both red light and infrared light are used to measure oxygen levels in the blood.

Figure 7: Max30100

When the heart pumps blood, there is an increase in oxygenated blood as a result of having more blood. As the heart relaxes, the volume of oxygenated blood also decreases. By knowing the time between the increase and decrease of oxygenated blood, the pulse rate is determined. It turns out, oxygenated blood absorbs more infrared light and passes more red light while deoxygenated blood absorbs red light and passes more infrared light. This is the main function of the MAX30100: it reads the absorption levels for both light sources and stores them in a buffer that can be read via I2C communication protocol.

Potentiometer

A potentiometer is a device that allows you to adjust the resistance in a circuit by moving a sliding or rotating contact along a resistive element. A potentiometer can be used to control the voltage, current, or signal level in a circuit. A potentiometer has three terminals: one connected to the input voltage source, one connected to the output voltage, and one connected to the sliding or rotating contact.

The output voltage depends on the position of the contact on the resistive element. A potentiometer can act as an adjustable voltage divider or a variable resistor. A potentiometer can be used for various applications, such as dimming lights, adjusting volume, measuring potential difference, and calibrating instruments.

Figure 8: Potentiometer

A potentiometer can also be used as a sensor to measure the position, angle, or displacement of an object. A potentiometer is a useful component for your project, as it can help you to fine-tune the parameters and performance of your portable ventilator. For example, you can use a potentiometer to set the desired tidal volume, respiratory rate, inspiratory pressure, or oxygen concentration for your ventilator. You can also use a potentiometer to monitor the feedback signals from the pressure sensor, the flow meter, or the volume indicator on your ventilator. A potentiometer is a simple and versatile component for your project, as it can provide you with manual control and adjustment of your portable ventilator.

POWER PACK

A power pack is a device that provides electrical energy to the ventilator, allowing it to operate without being plugged into a wall outlet. A power pack is essential for your project, as it enables you to use your ventilator in situations where mains power is not available, such as in remote areas, during power outages, or on the go. A power pack can also serve as a backup power source in case of an emergency, ensuring that your ventilator can continue to deliver life-saving ventilation to the patient.

Figure 9: Power Pack

The function of a power pack in your project is to supply electrical energy to your portable ventilator, so that you can use it anywhere and anytime you need it. A power pack also gives you peace of mind that your ventilator will not stop working in case of a power failure or interruption. A power pack is a vital component of your project, as it ensures that your ventilator can provide reliable and continuous ventilation to the patient.

2.2 Performance Evaluation Metrics

Pressure Calculation:
To calculate the pressure (P) in kPa that the ventilator delivers to the patient's lungs, the following formula is employed (Hussain *et al.*, 2018).

$$P = (V * R) / T \qquad (1)$$

Where V is the volume in liters, R is the gas constant (8.314 J/mol K), and T is the temperature in kelvins.

Volume Calculation:
To calculate the volume (V) in delivered to the patient's lungs, the formula used is:

$$V = (P * T) / R \qquad (2)$$

where P is the pressure in kPa, R is the gas constant (8.314 J/mol K), and T is the temperature in Kelvins.

Potentiometer Value Calculation:
To calculate the potentiometer value (PV) in ohms corresponding to a given pressure or volume, the following formula is applied: This was actually derived from the basic Ohm"s law.

$$PV = (P \text{ or } V * R1) / (R2 - P \text{ or } V) \qquad (3)$$

Where P or V is the pressure or volume in kPa or liters, R1 is the resistance of the potentiometer in ohms, and R2 is the maximum resistance of the potentiometer in ohms.

Pressure or Volume Calculation:
Conversely, to calculate the pressure or volume (P or V) in kPa or liters corresponding to a given potentiometer value, the following formula is utilized:

$$P \text{ or } V = (PV * R2) / (R1 + PV) \qquad (4)$$

Where PV is the potentiometer value in ohms, R1 is the resistance of the potentiometer in ohms, and R2 is the maximum resistance of the potentiometer in ohms.

RESULTS AND DISCUSSION

Performance Evaluation
Our ventilator design incorporates both volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV) methods. VCV delivers a fixed amount of air to the patient's lungs, while PCV delivers air until a specific pressure is reached. This dual approach provides flexibility based on patient needs and respiratory characteristics. The system, controlled by an

Arduino microcontroller, effectively compresses the bag-valve-mask (BVM) using a cam mechanism.

Design and implementation of a portable ventilator with variable BPM of the Result

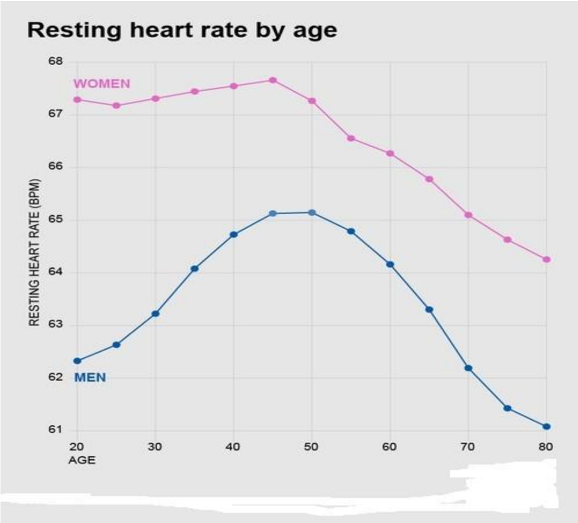

Figure 10: Performance Evaluation

Mechanical Design; The outer framework is successfully done using wooden pipes and joints which ensures lightweight, and a more portable design.
The frame was built with plywood, measuring 40 x 30 x 20 cm and weighing 9 lbs (4.1 kg). It was powered by a 12 VDC battery/

Figure 11: Frame Structures

Control Circuit; the ventilator system is will be controlled using Arduino microcontroller. This project will also contain features that monitor the patient's blood oxygen level and lung strain during exhalation, to prevent any potential issues related to gas tension. Our aim is to develop a cost effective and portable ventilator that can be used during times of pandemics (covid-19) and other emergency situations.

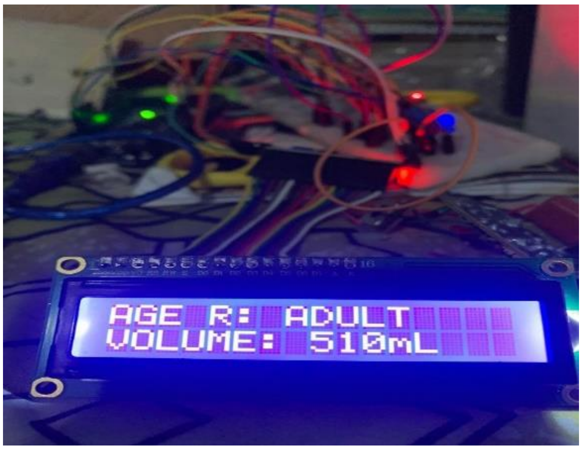

Figure 12: Led display screen

Usability Assessment
The usability of our portable ventilator is enhanced by a user-friendly control panel, allowing adjustments to ventilation parameters such as tidal volume, respiratory rate, and pressure relief valve. Additionally, the incorporation of a battery pack ensures device functionality during emergencies. A LED display screen provides real-time feedback on critical patient signs, including oxygen saturation, heartbeat rate, and blood pressure.

Safety Analysis
Ensuring patient safety, our ventilator includes features monitoring blood oxygen levels and lung strain during exhalation, mitigating potential issues related to gas tension. This safety-oriented design aligns with contemporary standards and regulatory compliance as compare to (Lacerda *et al*., 2017).

Results validation is as discussed in sections 3.1 to 3.3 above. Under performance evaluation according to the American Heart Association, a normal resting heart rate is between 60 (beats per minute) and 100 (beats per minute) for people 15 years and older. Nevertheless, a low heart rate can also be common in athletes, people who are physically fit, or people who take medications such as beta-blockers. Usability analysis helps in a led display screen which provide real time feedback on critical patient.

CONCLUSION
In the realm of respiratory care, the portable variable ventilator emerges as a groundbreaking innovation, offering a ventilation strategy that surpasses conventional modes. Our findings underscore its effectiveness in providing enhanced and protective ventilation for patients grappling with conditions like Acute Respiratory Distress Syndrome (ARDS) or other pulmonary ailments. Beyond its clinical advantages, the portable variable ventilator brings with it the benefits of portability – ease of use, mobility, and cost-effectiveness.

This portable device not only has the potential to diminish the reliance on invasive ventilation but also serves as a catalyst for early extubating, thereby mitigating extubating failure risks and circumventing the need for reintubation in high-risk patient groups. The improved patient outcomes extend to enhanced comfort and an elevated quality of life, as the portable variable ventilator promotes spontaneous breathing and reduces the necessity for sedation.

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