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Portable Smart Ventilator with AI Control

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Abstract: The rising number of cases of respiratory diseases and emergency care cases have distinguished the necessity of inclusive and effective mechanical ventilator solutions, particularly in place of limited resources. Traditional ventilators are usually expensive, complicated and unable to be deployed quickly thus being inaccessible in rural hospitals and emergency medical centers. The given paper describes the development and testing of the new low-cost microcontroller-based ventilator system that will be used on emergency and basic critical-care. The suggested system will incorporate pressure and airflow sensors that will constantly check the respiratory parameters of the patient and a motor-driven mechanism that will control the inhalation and exhaled phases. The main control unit is a microcontroller, which is able to process real-time data, create closed-loop control, and dynamically adjust the parameters of ventilation, e.g., breathing rate and tidal volume. Safety has been increased by built-in alarm systems to notify the medical staff in case of abnormal pressure or airflow. Ventilator is made to be small in size, low-energy consuming, and easy to use making it easy to deploy and operate. The results of the simulation and functional validation prove the stable and reliable operation and the system is a cost-effective and feasible option to be used in the emergency respiratory support in low-resource healthcare settings.

Keywords: *Ventilator, Emergency Healthcare, Embedded Systems, Mechanical Ventilation, Biomedical Devices, AI.*

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I. INTRODUCTION

The importance of mechanical ventilation is significant in patients affected by respiratory failure, trauma and severe pulmonary disorders. The increasing rate of respiratory diseases, contagious outbreaks, and emergency medical cases have greatly contributed to the world demand of ventilator systems. The traditional ventilators are the most common among the intensive care units and have advanced monitoring and control equipment. Nevertheless, the systems are costly, large, and need the presence of skilled individuals to operate. In developing and resource-constrained areas, no access to ventilators is affordable, which limits the availability of the necessary respiratory care, especially in crisis situations and in large-scale health emergencies. Current studies and commercial ventilator products are mainly centered in high end, feature rich ventilator products aimed at high end hospital back infrastructure. There has been little focus on the development of low cost ventilators that compromise on affordability, safety and functionality. Most of the emergency ventilator prototypes are not provided with the control of real-time feedback, monitor patient safety or can be scaled to be applied in practice. Also, not many designs respond to the necessity to make operation simplified without the need to jeopardize the necessary ventilation parameters. This forms a great research gap in developing a low-cost, small-sized, and efficient ventilator system that is able to deliver controlled respiratory support without jeopardizing patient safety in low-resource healthcare settings. This project is motivated by the necessity to enhance the level of access to life-saving respiratory assistance in case of medical emergency. The problem of the shortage in ventilators is most common in rural and underdeveloped areas, which are usually caused by phenomena like pandemics, natural disasters, and mass casualty incidents.

The establishment of a cheap and simple to use ventilator can contribute to a considerable decrease in reliance on costly imported systems and increase emergency preparedness. Moreover, the development of embedded systems and sensor technologies opens up a possibility to develop efficient ventilators with the help of the components that are easy to access. The rationale behind this project is to provide a viable and cost-effective solution that does not

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interfere with patient safety. The development of an inexpensive ventilator has a number of technical and functional problems. The correct monitoring of airflow, pressure, and breathing cycles with keeping the patient safe are critical issues. The system should also be able to manage the changes in the respiratory status of patients without barotrauma and inadequate ventilation. With inexpensive sensors and microcontrollers, close loop control has to be carefully calibrated and algorithm designed. Also, the design constraints are high due to minimization of the complexity of the system and at the same time, the system has to be robust, energy efficient and have reliable alarms. One of the greatest issues that have been tackled in this project is balancing low cost and the necessity to meet the necessary medical safety standards. This project is limited to the design and development of a low-cost ventilator that can be used during emergencies and basic critical-care settings. The system will ensure the provision of controlled ventilation with adjustable breathing parameters, real-time monitoring, and safety alerts. It will be used in rural hospitals, temporary hospitals, and emergency response teams and not in sophisticated ICU units. Affordability, portability, and ease of operation are the main points of the project.

The subsequent extensions can be related to the IoT-based remote monitoring, data logging, and incorporation of sophisticated control algorithms to increase the flexibility and efficiency of the system.

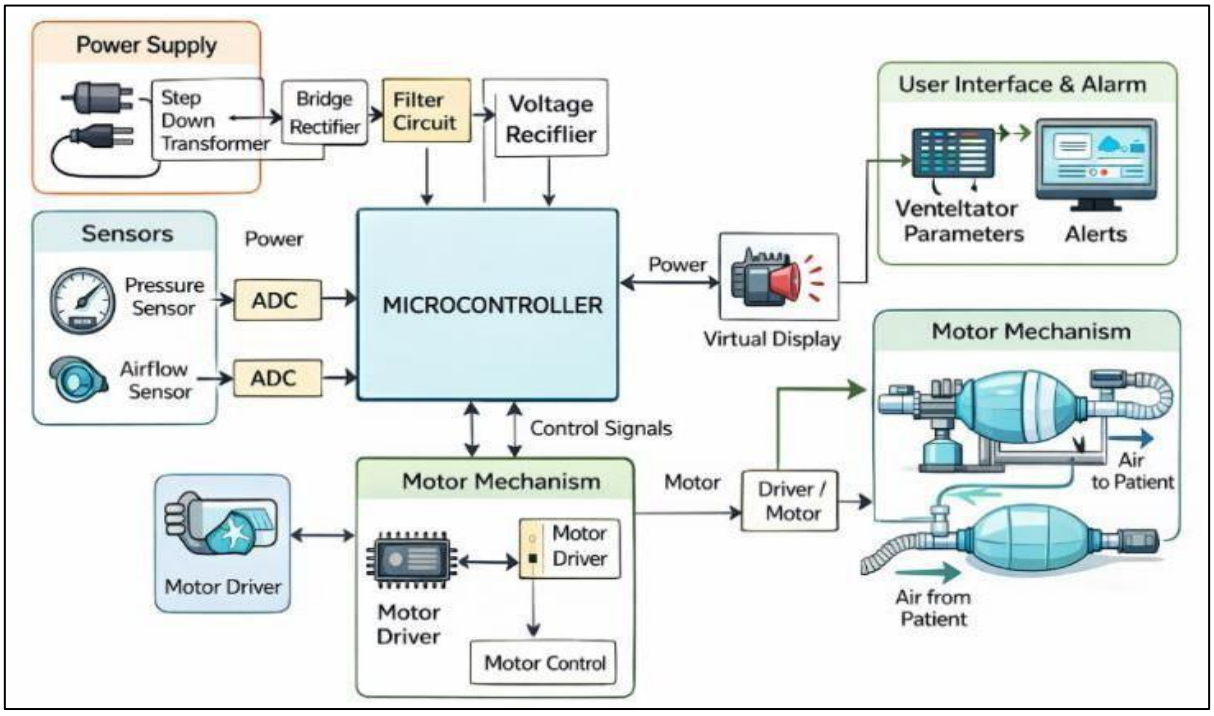


Fig 1 System Architecture

II. LITERATURE SURVEY

The COVID-19 pandemic showed the world the critical lack of ventilators, with a particular shortage in low- and middle-income countries. This crisis has increased the speed of the design of low-cost, portable, and fast deployable ventilator systems. A number of studies have been aimed at making mechanical ventilators inexpensive but able to provide controlled respiratory support at the same time without compromising on patient safety. The initial portable ventilator designs focused on simplicity, cost-effectiveness and ease of assembly with components that are locally available [1], [3]. These systems mainly automated manually resuscitated bag, or applied simple mechanical compression to provide a regulated tidal volume and respiratory rate. Non-invasive electromechanical ventilators that are cheap, possessing feedback to enhance accuracy and stability were also suggested [2].

These systems were fitted with pressure and flow sensors to stabilize the airway pressure and provide a constant supply of oxygen. Introduction of closed-loop feedback control was a great breakthrough compared to purely mechanical systems as it gave the opportunity to continuously monitor and adjust ventilation parameters. Nevertheless, their systems were mostly based on controlling strategies that were based on thresholds and not adaptive intelligence. Non-invasive ventilators with patient monitoring systems were designed in response to homecare and remote monitoring requirements [4]. Such systems incorporated real time measurements of such parameters as airway pressure, respiratory rate, oxygen saturation and tidal volume. Monitoring modules enabled remote control and data record keeping, which is in line with the rising trend of smart medical technologies. However, the majority of the applications were based on automating hardware and low-level sensor integration without sophisticated predictive analytics. Recent studies have also focused on using oxygen generation units as part of the ventilator systems in order to improve portability and lack of dependence on hospital oxygen supplies [5].

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The history of the scroll compressor-based oxygen generator-integrated ventilators shows that it is possible to develop compact and self-sufficient respiratory support systems. In spite of these developments, smart control of oxygen supply with reference to patient demands is minimal. In emergency ventilations during the pandemic, automated resuscitator bag systems were designed, which can be deployed very quickly [6], [14], [16]. These systems were concerned with fast development rate, open-source availability and emergency usability. Pulmonary monitored open-source mechanical ventilators were also introduced to facilitate openness and joint development [10]. The support of microcontroller-based systems where the implementation is supported by Arduino and other platforms also showed that inexpensive embedded systems could be utilized to automate the process of ventilation and measure some simple parameters [12]. On the same note, the idea of PLC-based control systems was investigated as a means of reliable and automation of industrial grade [8]. The adjustment of the ventilator to safe operation requires sensor precision and alarm systems. Sensor and alarm algorithms were suggested with low complexity to identify abnormal pressure, flow anomalies, and system errors [11]. Sensing of tidal volume was also invented using the techniques of differential pressure spirometry in case of emergency ventilators [20]. These contributions made patient safety better, as far as they guaranteed good parameter measurement and fault detection in time.

Most systems however did not have intelligent systems of anomaly detection but instead relied on rule based alarms. There was also an introduction of portable ventilator designs with a lot of focus on simplicity and ease of construction to respond to the pressing healthcare requirements [13], [17]. The complexity and cost of the components were reduced in these systems and they could be used in quick production in the case of health emergency. There were also more extensive clinical reviews that have given significance to non-mechanical ventilation interventions such as non-invasive positive pressure ventilation and extracorporeal membrane oxygenation (ECMO) in critically ill patients [18], [19]. In these studies, it is emphasized that the most effective approach that the organization in question should employ to ensure the efficiency of the current ventilators is the flexibility of their ventilation modes, which will react to the changes in patient conditions. Even though much advancement has been achieved in the area of the low-cost ventilator hardware design, automation, and sensor combination, most current systems are based on fixed control logic or manually programmed parameters. The conventional ventilators usually compel clinicians to change tidal volume, inspiratory/expiratory ratio, respiratory rate, and pressure boundaries depending on the response of the patient. This cable reliance can cause delays in parameter optimization particularly in resource limited surroundings. The use of Artificial Intelligence (AI) in portable ventilator devices is one way to eliminate such drawbacks. The AI-controlled systems will be able to process real-time patient information, learn how to breathe, and vary the ventilation to keep the respiration as effective as possible.

The machine learning algorithms can also be used to predict possible respiratory deterioration by detecting trends in the data on pressure, flow, and oxygen saturation. Moreover, AI-based anomaly detection will be used to improve alarm systems because it will be capable of differentiating between non-persistent fluctuations and clinically relevant events and will minimize false alarms. To conclude, the current literature proves the significant attempts at the creation of affordable, portable, and sensor-equipped ventilators. Technology has provided a solid footing with technological advances in mechanical automation, microcontroller-based control, integration of oxygen generation and safety monitoring. Nevertheless, few studies have been conducted on the integration of smart adaptive control systems into portable ventilator systems. The gap can be closed with a Portable Smart Ventilator with AI Control, comprising affordable hardware, superior sensing, real-time analytics, and machine learning-enhanced adaptive control to enhance the performance of patient-specific ventilation, safety, and clinical outcomes.

- *Problem Statement*

The issue of the availability of reliable mechanical ventilators is a serious problem in healthcare facilities that are subjected to emergencies and scarce resources. Traditional ventilator systems are costly, complicated and need unique infrastructure and skilled staff and therefore cannot be deployed quickly in rural hospitals, temporary medical units and extensive emergencies. The supply of ventilators is usually outdone by the high demand of ventilators during health crises, thus patients with breathing failure receive insufficient respiratory support. The available cheap substitutes often do not have real-time monitoring, do not allow adjusting ventilation parameters as precisely as possible, and do not have the necessary safety mechanisms, which puts patients at risk of injuries. Thus, the current need is an affordable, small, and efficient ventilator system able to provide controlled respiratory support with fundamental monitoring and safety measures and be easy to use and implement in the emergency medical environment.

- *Existing System*

The current mechanical ventilator systems are mostly equipped to operate in highly developed hospital settings, especially in the intensive care units, whereby advanced infrastructure and trained medical staff are present. These systems will offer accurate regulation of ventilation settings which include tidal volume, airway pressure and respiration rate as well as sophisticated monitoring and alerting. The commercial ventilators are however costly, cumbersome and need constant care, which restricts their usage in the rural and resource strained health care environments. In emergency cases and epidemic outbreaks of large scale health problems, the expensive nature and the scanty number of the traditional ventilators may lead to severe shortages. In addition, their complicated functionality and reliance on constant power and technical assistance limit their use in temporary and emergency medical facilities.

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III. METHODOLOGY

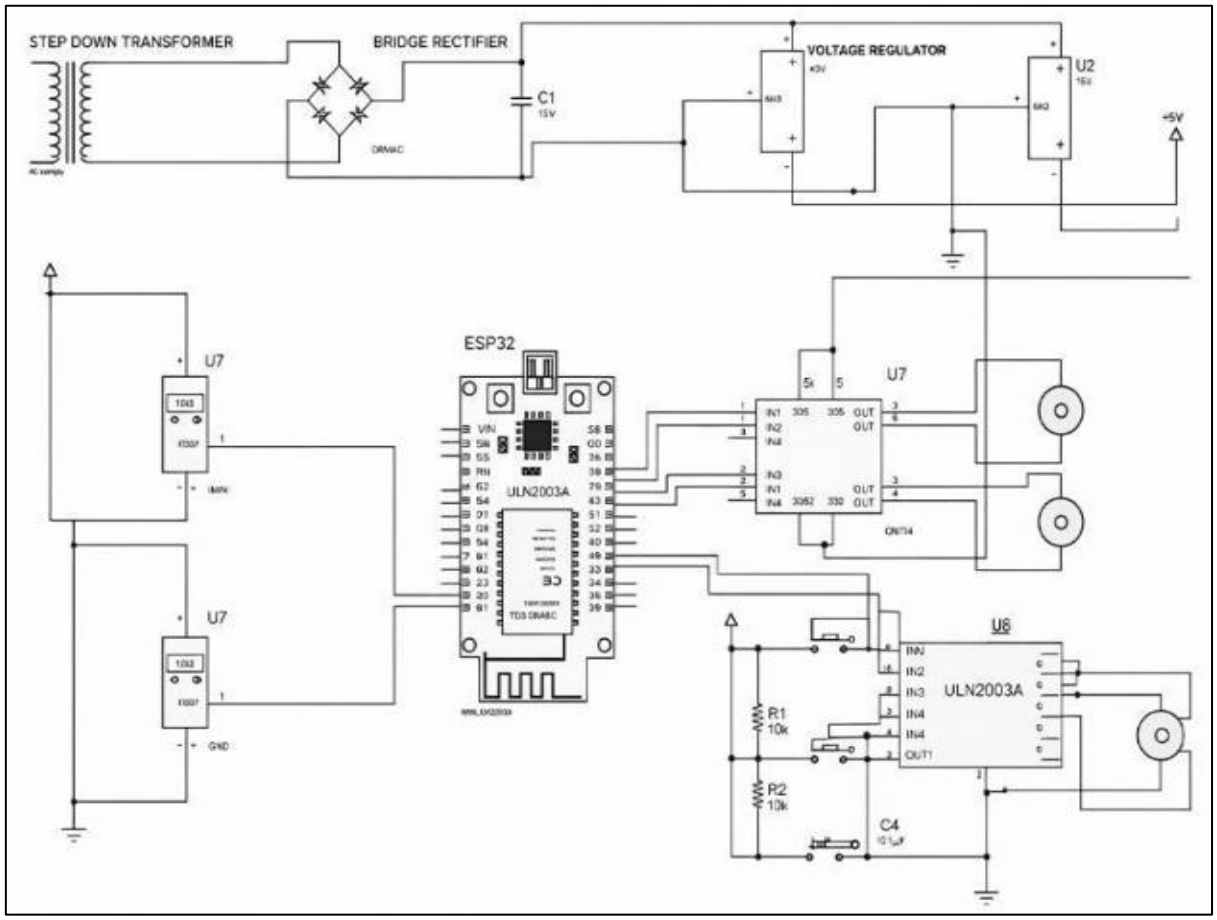


Fig 2 Circuit Diagram

➢ *Sensor Module*

The sensor component will have the task of obtaining real-time respiratory data on the patient. Airway pressure and rate of air delivery during the inhalation and exhalation are measured using the pressure sensors and airflow sensors. These sensors will offer real-time information about the efficiency of ventilations, allowing one to monitor the respiratory rate of patients correctly. The data experienced is conditioned and sent to the control unit to be processed further. Low-cost sensors are used to guarantee low costs, but acceptable accuracy and responsiveness that are necessary in ensuring safety in ventilation control.

➢ *Control and Processing Module*

The control and processing module is constructed on a microcontroller which is the central part of the system. It takes into consideration real-time information provided by the sensor module and implements control algorithms to control the ventilation process. The microcontroller provides control signals to the actuation unit based on the set and adjustable parameters including the breathing rate and tidal volume. This module allows closed-loop control of the ventilation that ensures the stability of the ventilation and adaptive response to changes in respiratory conditions of patients.

➢ *Ventilation Actuation Module*

The ventilation actuation mode comprises of motor-powered mechanical system that regulates the inhalation and exhalation processes. The control module controls the windings of the motor operation by means of a motor driver circuit and is enabled to provide accurate delivery of timing and airflow. This module also moves the air delivery system by compressing and releasing it physically to mimic the natural breathing pattern. The structure guarantees free-flowing of air, less mechanical stress, and uniform ventilation functioning comfortably in case of emergency respiratory assistance.

The ventilation actuation module comprises of a mechanical system which is controlled by a gear motor and is used to control inhalation and exhalation. The motor with the help of motor driver circuit moves a linear actuator to compress and release the air chamber and mimics the natural breathing. The force that is produced by the actuator is:

$$F=k\cdot x$$

Where k is the stiffness factor and x is the displacement.

The work of the gear motor is founded on the electromagnetic principles. Torque generated by the motor is given as:

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$(\alpha)=B\cdot I\cdot L\cdot w\cdot \cos\alpha$

Where,

B = magnetic flux density,

I = armature current,

L = conductor length,

Where, w = width of the armature,

2 = the angular position of the rotor.

Torque is greatest at 0 ° and (τ = BILw) therefore the motor is able to overcome initial inertia. Torque varies with cosalpha such that it becomes zero at 90 ∘ and then rises as a result of continuous rotation.. The current that is needed on the motor is determined as:

$I= B\cdot L\cdot w\cdot \cos\alpha$

These equations make the motor to be properly sized and functioning to generate the consistent airflow.

➢ *Safety and Alarm Module*

The safety and alarm module will improve the safety of patients by monitoring the output of systems and sensors all the time. The module triggers audible and visual alarms should abnormal conditions like high airway pressure, uneven airflow or system malfunction be detected. Such alarms alert medical staff to do remedial measures. The module is imperative in averting patient harm and adherence to vital medical safety standards, especially during unattended or emergency cases.

➢ *User Interface and Display Module*

Display module and user interface can give a real-time picture of the ventilation parameters like the pressure levels, the state of airflow, and the rate of breathing. An easy to use display unit and control inputs enable the medical personnel to check on the performance of the system and its ventilation settings without a lot of effort. The interface is made user-friendly so that one may not require specific training. The module enhances the usability and allows working in the emergency and resource-restricted healthcare setting.

➢ *Power Supply Module*

The power supply module provides regulated power supply to the system components. It has voltage regulation and protection circuits in order to maintain stable and safe work of sensors, control units, and actuators.

The system has been designed to have a low power consumption with an option to be expanded to have a battery backup that facilitates continuous use in case of electrical outages. The module improves the reliability and emergency deployment viability of the systems.

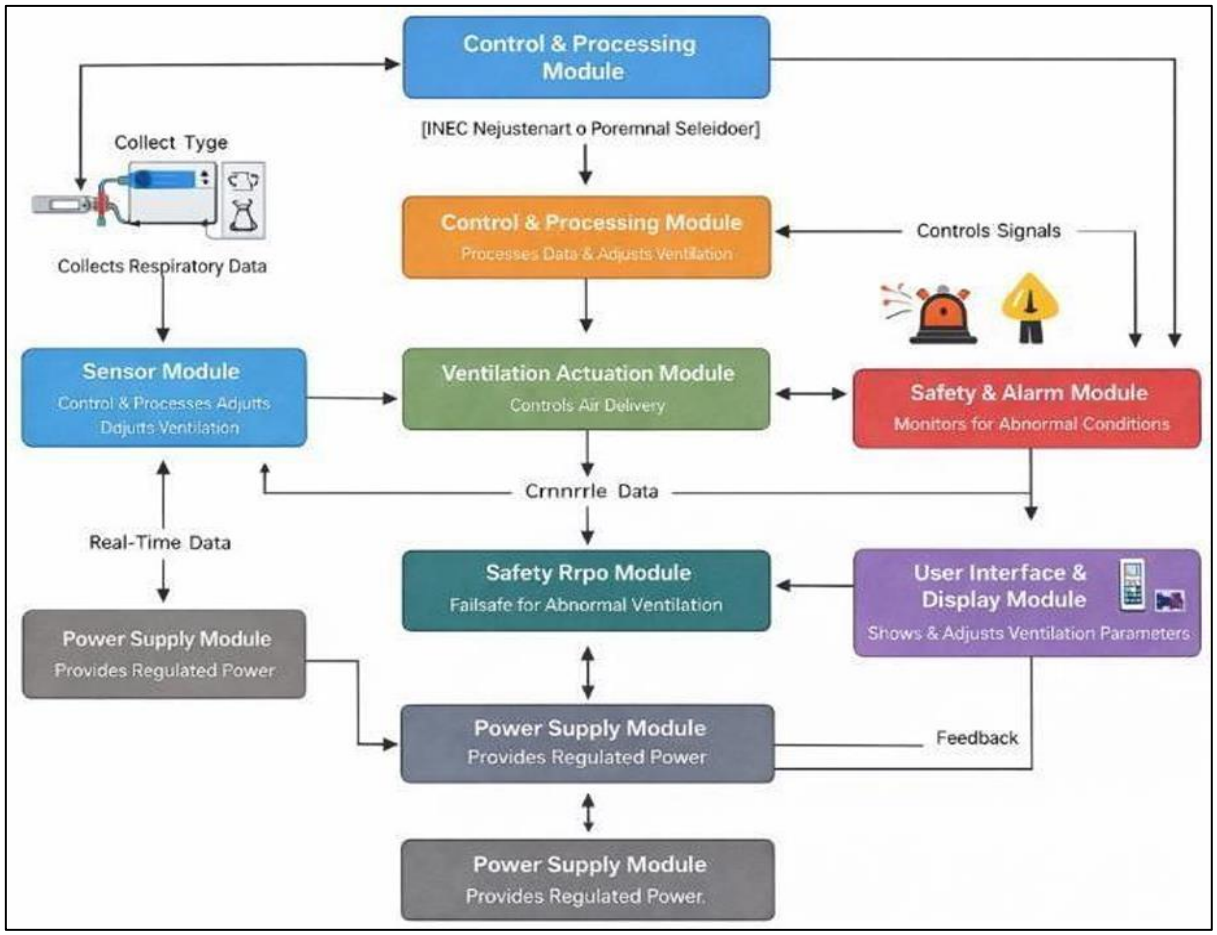


Fig 3 Flow Chart

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➢ *Proposed System*

The presented system presents a new low-cost mechanical ventilator that is aimed at delivering the necessary respiratory support under emergency and resources scarce conditions in medical care.

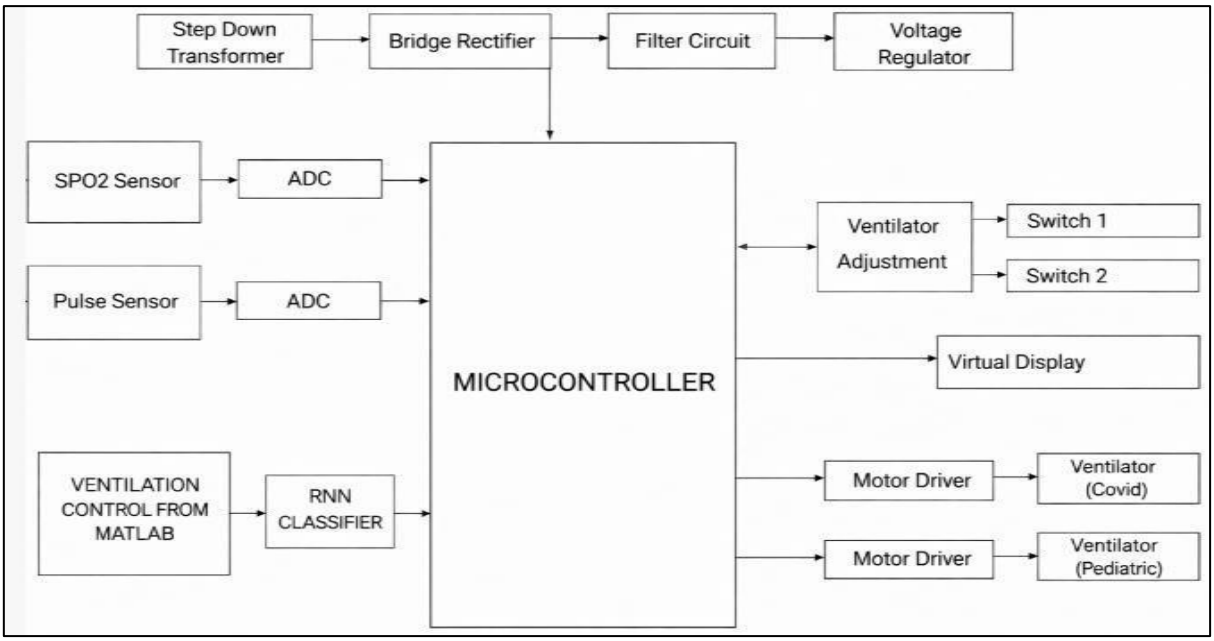


Fig 4 Block Diagram

The system is designed on the basis of a microcontroller-based control unit that controls the ventilation cycles with an aid of a motor-powered mechanism which allows the control of inhalation and exhalation. The sensors of pressure and air flow are also incorporated to ensure that the respiratory parameters of the patient are continually checked and real-time feedback is provided. Variable ventilator parameters like the breathing rate and tidal volume can be adjusted to various needs of the patient. It is also safe with built-in alarm system to alert the medical staff whenever there is abnormal pressure or airflow. Its small size and low power usage, combined with user-friendly design, allows easy deployment and the proposed ventilator can be used as a convenient and affordable alternative to the traditional systems in emergency and basic critical-care settings.

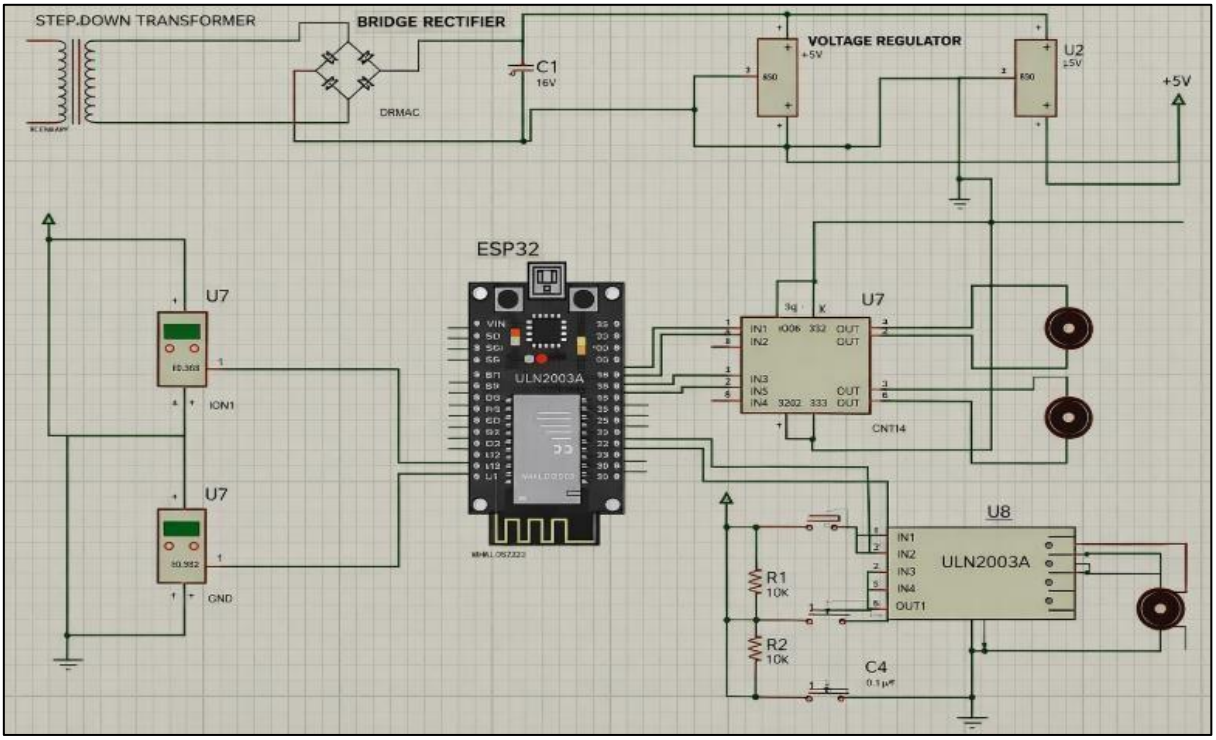


Fig 5 Simulation

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IV. RESULT AND DISCUSSION

The low-cost ventilator system suggested was realised with the help of using microcontroller-based control unit, pressure and airflow sensors, motor driver circuit, and motor-driven ventilation mechanism. The sensors were checked so that it was time-specifically correct in that airway pressure and airflow was measured during inhalation and exhalation. The microcontroller was coded to perform real-time control algorithms to control the breathing rate and tidal volume depending on predefined parameters. An alarm system and display were connected to monitor the system in real time and raise alarms in case of safety concerns. All the parts were assembled into a miniature system that can be easily moved and deployed. Controlled testing of systems was done to ensure stability of the system and responsiveness.



Fig 6 Hardware Prototype

The system was able to maintain the required rate of breathing and regulate the airflow within safe pressure parameters.



Fig 7 Blynk Output

The experiment findings confirm that the ventilator system, which is applied, can ensure the stable and consistent ventilation under various operating conditions. The sensor feedback provided pathways to the correct identification of the pressure variations, and the alarm module was in time to respond to the abnormal situations like the overinflation of the airways. The Ventilator consumed low power and exhibited consistency in its performance when used continuously. The findings agree that the system is effective in providing the necessary respiratory support without compromising the safety and operational dependability.

Table 1 Comparison Between Existing and Proposed System

Feature/Aspect	Existing System	Proposed System
Target Environment	Advanced hospital ICUs	Emergency, resource-limited, rural healthcare
Cost	High	Low-cost
Size & Portability	Large, cumbersome	Compact, portable
Power Requirement	Continuous, high	Low power, energy-efficient
Operation Complexity	Requires trained medical staff	User-friendly, easy to operate
Ventilation Control	Accurate, fully adjustable	Adjustable breathing rate and tidal volume
Monitoring & Safety	Sophisticated monitoring & alerts	Real-time feedback with pressure/airflow sensors, built-in alarm

The results gained justify the possibility to create a reliable ventilator based on low-cost products without negatively affecting the critical safety aspects. The proposed system can be compared to the conventional ventilators in terms of reduced complexity, a higher level of portability and much less costs, which makes this system suitable in the emergency or resource-limited healthcare facilities. Although the system does not substitute advanced ICU ventilators, it is very useful in meeting critical ventilation requirements in an emergency. The future has seen the potential to increase sensor accuracy, control algorithms, and remote monitoring to increase performance and scalability.

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V. CONCLUSION

The presented paper described the design and development of a new low-cost mechanically based ventilator, which is aimed at emergency and resource-constrained healthcare settings. The proposed system unites pressure and airflow sensors with a microcontroller-based control unit in providing controlled and reliable respiratory support. The experimental analysis showed a steady ventilation performance, good ability to monitor respiratory parameters, and safety warnings in time during abnormal operating conditions. The small size, minimal power use and easy mode of operation make the system applicable in quick implementation within the rural hospitals, temporary medical and emergency response situations. Though the proposed ventilator is not designed to replace more sophisticated ICU-grade ventilators, it is a good solution to the urgent requirement to have an accessible respiratory aid in case of an emergency. Additional future improvements can be advanced closed-loop control approaches, wireless monitoring, and sensor accuracy to gain additional reliability and clinical applicability. Overall, the suggested solution provides a practical, cost-effective, and scalable way of enhancing emergency respiratory care.

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