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Smart Portable Ventilator with Real-Time Blood Oxygen Monitoring for Affordable Respiratory Support

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Abstract

The global surge in respiratory illnesses, particularly due to the COVID-19 pandemic, has intensified the demand for ventilatory support. However, conventional ventilators are often costly, bulky, and challenging to access in low-resource settings. This paper introduces the development of a Smart, Lightweight, and Portable Ventilator with Integrated Real-Time Blood Oxygen Monitoring, designed to deliver effective and affordable respiratory assistance. The proposed system utilizes a motor-driven mechanism to automate the compression of an Ambu bag, ensuring a consistent and controlled airflow for patients in critical need. A key feature of this ventilator is its real-time blood oxygen monitoring capability, achieved through an integrated pulse oximeter sensor. This enables continuous tracking of oxygen saturation (SpO_2) levels, allowing for timely interventions and enhanced patient safety. With a compact and lightweight design, the device is highly portable, making it well-suited for emergency scenarios, remote healthcare facilities, and areas with limited access to advanced medical equipment. By combining affordability, portability, and intelligent oxygen monitoring, this innovative solution addresses the urgent need for accessible ventilatory support, particularly in underserved regions. The proposed system has the potential to improve patient care and expand the availability of respiratory support worldwide.

1. Introduction

The COVID-19 pandemic has significantly increased the global demand for mechanical ventilators, which are essential for managing severe respiratory distress conditions. In 2019, the global ventilator market was valued at approximately USD 2.54 billion, with projections indicating growth to USD 12.14 billion by 2032, at a compound annual growth rate (CAGR) of 5.3%. This rise is driven by the increasing prevalence of respiratory diseases such as acute respiratory distress syndrome (ARDS), chronic obstructive pulmonary disease (COPD), and pneumonia, which require ventilatory support for effective treatment [1]. However, many low- and middle-income countries (LMICs) have faced ventilator shortages, exacerbating healthcare crises, particularly during the pandemic. The high cost, bulky design, and complex operation of conventional ventilators further limit accessibility, underscoring the need for affordable, portable, and efficient alternatives [2]. Traditional ventilators, while effective, present challenges in terms of size, weight, and affordability. For instance, the HAMILTON-T1 transport ventilator weighs approximately 6.5 kg (14.3 lbs) with dimensions of 320 × 220 × 270 mm, while the Newport HT70 Plus ventilator weighs about 6.9 kg (15.4 lbs) and measures 9.75 × 11 × 10.25 inches. The heavy and bulky nature of these ventilators makes them impractical for use in emergency transport, disaster relief, and remote healthcare facilities. Additionally, the high procurement and maintenance costs limit their deployment in resource-limited settings. These challenges highlight the need for an alternative ventilation system that is lightweight, cost-effective, and capable of providing reliable respiratory support in diverse healthcare environments [3]. To address these issues, this paper presents the development of a Smart, Lightweight, and Portable Ventilator with Integrated Real-Time Blood Oxygen Monitoring. The proposed system automates the compression of an Ambu bag (self-inflating resuscitator) through a motorized mechanism, ensuring consistent and controlled airflow to patients. Unlike traditional ventilators, this system integrates a pulse oximeter sensor for continuous blood oxygen saturation (SpO_2) monitoring, allowing real-time assessment of a patient's oxygen levels. SpO_2 monitoring is crucial in detecting hypoxia early, enabling immediate adjustments to ventilation parameters to prevent complications such as tissue hypoxia, respiratory failure, and organ dysfunction [4]. This real-time feedback mechanism enhances patient safety, optimizes oxygen delivery, and ensures timely medical interventions, making the ventilator an intelligent and adaptive system for respiratory care. The necessity of SpO_2 monitoring in ventilator systems is further reinforced by studies showing that unmonitored oxygen therapy can lead to hyperoxia (excess oxygen levels), which increases the risk of oxidative stress, lung injury, and cardiovascular complications [5]. In emergency and low-resource settings, where healthcare professionals may have limited access to advanced monitoring equipment, integrated SpO_2 tracking allows for more precise and automated regulation of oxygen delivery, reducing manual intervention and improving patient outcomes. Additionally, incorporating real-time blood oxygen monitoring enhances the efficiency of the ventilator in critical care scenarios, home-based respiratory therapy, and pandemic preparedness, ensuring effective respiratory support across various clinical applications [6].

2. Literature Survey

Several studies have investigated the development of portable ventilators to address the increasing global demand for accessible and cost-effective respiratory support [7]. Traditional ventilators, while effective, are often expensive, cumbersome, and reliant on specialized infrastructure, limiting their deployment in resource-constrained settings. AI-driven diagnostic tools have demonstrated significant potential in enhancing respiratory monitoring, particularly for conditions such as chronic obstructive pulmonary disease (COPD), pneumonia, and acute respiratory distress syndrome (ARDS). Advanced deep learning models, including convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have shown high accuracy in lung sound classification, facilitating early detection and intervention [8]. However, real-time implementation remains challenging due to variations in lung sound recordings, environmental noise interference, and the need for extensive annotated datasets. Blood oxygen saturation (SpO_2) monitoring is a critical component of modern ventilator systems, ensuring real-time assessment of a patient's oxygenation status. Studies indicate that SpO_2 levels falling below 90% can lead to severe hypoxemia, increasing the risk of respiratory failure and multi-organ dysfunction. Conventional ventilators often rely on external pulse oximeters for oxygen saturation measurement, which may introduce delays in adjusting ventilation parameters. Integrating SpO_2 sensors directly into ventilator systems enables continuous monitoring, ensuring dynamic oxygen therapy adjustments based on real-time physiological feedback [9]. AI-driven SpO_2 monitoring has demonstrated improved patient outcomes by optimizing ventilation support, minimizing complications, and reducing the burden on healthcare professionals. The Internet of Things

(IoT) has emerged as a transformative technology in respiratory care, enabling real-time remote monitoring and cloud-based data management for ventilator systems. IoT-enabled ventilators facilitate continuous tracking of critical parameters such as respiratory rate, tidal volume, and oxygen saturation, allowing clinicians to make informed decisions regardless of geographical constraints. Research has highlighted the advantages of IoT-driven ventilatory support in improving accessibility, particularly in rural and underserved areas with limited access to pulmonologists. The integration of cloud computing enhances data storage, remote accessibility, and predictive analytics for early detection of respiratory distress. However, challenges related to data security, connectivity reliability, and device interoperability must be addressed for seamless clinical implementation. Despite significant advancements, AI-powered ventilators still face technical and regulatory challenges that limit their large-scale deployment. Variability in lung sound recordings, differences in auscultation techniques, and background noise interference can affect the accuracy of AI-based diagnostic models. Furthermore, the scarcity of high-quality, well-annotated lung sound datasets poses a challenge for training robust deep-learning algorithms, limiting their generalizability. Ethical considerations surrounding patient data privacy, cybersecurity risks, and regulatory compliance further complicate the integration of AI and IoT into clinical ventilator systems. Addressing these challenges requires interdisciplinary research efforts to enhance model reliability, standardize data acquisition protocols, and establish ethical AI frameworks for medical applications. Future developments in AI-integrated ventilator technology should focus on enhancing automation, affordability, and accessibility for diverse healthcare environments. The incorporation of adaptive ventilation mechanisms, combined with AI-powered real-time SpO_2 monitoring, can optimize patient-specific respiratory support. Additionally, AI-driven digital stethoscopes with lung sound classification capabilities can complement ventilator systems by enabling early disease detection and improving diagnostic precision. Expanding cloud-based telemedicine applications will further enhance remote patient management, allowing for real-time clinician intervention and reducing hospital admissions. Overcoming the existing technological and regulatory barriers will be crucial in realizing the full potential of AI and IoT in revolutionizing respiratory care and improving patient survival rates globally.

3. Proposed System

The proposed system is designed to enhance the management and monitoring of patients with respiratory conditions through a comprehensive, real-time tracking mechanism that continuously measures critical physiological parameters, including oxygen saturation (SpO_2), heart rate, and body temperature. By integrating advanced sensor technologies with a responsive feedback system, this innovative ventilator ensures that patients receive optimal oxygen delivery based on their real-time needs. The system addresses key challenges in respiratory care by providing accurate and timely physiological data, enabling healthcare professionals to detect early signs of deterioration and intervene promptly to prevent complications. The seamless integration of continuous monitoring enhances patient safety, reduces the risk of oxygen deprivation, and improves clinical decision-making in both hospital and home care settings. The MAX30100 pulse oximeter sensor is employed for the precise measurement of oxygen saturation (SpO_2) and heart rate, ensuring continuous evaluation of a patient’s respiratory and cardiovascular status. Monitoring SpO_2 levels is particularly crucial in detecting hypoxia, a condition that, if left unaddressed, can result in severe complications, including organ failure. Additionally, the system integrates the DHT11 sensor to measure body temperature, which is vital for the early detection of infections or febrile conditions that may exacerbate respiratory distress. By combining these sensors in a unified framework, the system facilitates real-time patient monitoring, enabling healthcare professionals to respond promptly to any deviations from normal physiological ranges (Figure 1). This continuous monitoring approach is particularly beneficial for patients with chronic respiratory disorders, such as chronic obstructive pulmonary disease (COPD) and asthma, who require vigilant supervision and timely medical intervention. At the core of the system, a microcontroller serves as the central processing unit, continuously acquiring and analysing real-time data from the MAX30100 and DHT11 sensors.

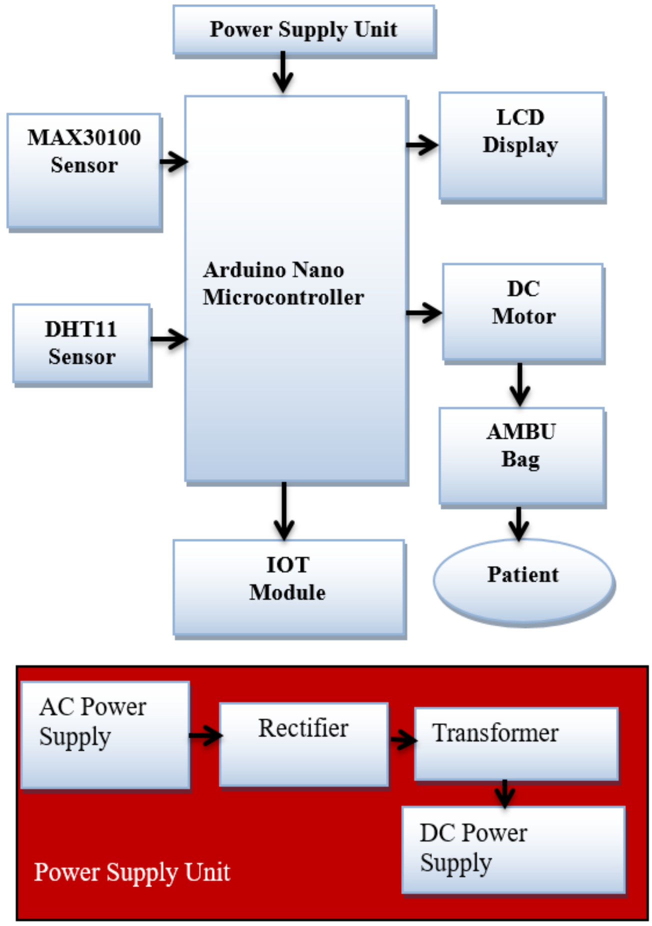

Figure 1 **Block Diagram**

If SpO_2 levels fall below a predefined threshold (95%), the microcontroller triggers an automated response, activating a DC motor to initiate mechanical ventilation. This motor-driven mechanism compresses a self-inflating AMBU bag, delivering oxygen-enriched air to the patient without requiring manual intervention. The automation of this process is particularly critical in emergency situations, where rapid oxygen administration is essential in preventing respiratory failure. By eliminating the reliance on human-operated ventilation, the system ensures timely respiratory assistance, reducing the risk of delays in life-threatening scenarios. The precision-controlled AMBU bag compression mechanism optimizes air delivery, preventing complications such as hyperventilation or barotrauma. This feature makes the system adaptable for both hospital-based intensive care and home-based patient management, particularly for individuals with progressive respiratory conditions. Furthermore, the integration of this automated ventilation mechanism minimizes human error and enhances efficiency, making it a reliable and scalable solution for improving patient outcomes. A vital aspect of the proposed system is the LCD display, which provides real-time visualization of key patient parameters, including SpO_2, heart rate, and body temperature. The availability of continuous on-screen monitoring is particularly beneficial in critical care environments, such as intensive care units (ICUs) and emergency departments, where immediate access to patient data is essential for timely interventions. The structured and user-friendly interface of the LCD enhances accessibility, allowing both medical professionals and caregivers to interpret vital signs with ease. Moreover, the LCD screen is programmed to generate visual alerts when any of the monitored parameters deviate from normal ranges, prompting immediate action. In home-care settings, this feature is particularly advantageous for caregivers managing generate visual alerts when any of the monitored parameters deviate from normal ranges, prompting immediate action. In home-care settings, this feature is particularly advantageous for caregivers managing patients with chronic illnesses, as it enables early detection of abnormalities, reducing the likelihood of medical emergencies (Figure 2). By incorporating a real-time display with alert mechanisms, the system enhances patient safety and fosters a proactive approach to respiratory care. The integration of an IoT module further enhances the functionality of the system by enabling continuous remote monitoring of patient health data. The IoT module transmits real-time SpO_2, heart rate, and temperature readings to a secure cloud-based platform, providing healthcare professionals with remote access via web-based or mobile applications. In addition to facilitating remote consultations, the IoT system generates automated alerts and notifications when critical physiological parameters exceed pre-set safety thresholds, ensuring that healthcare providers can intervene promptly. The ability to continuously store and analyse patient data over extended periods allows for trend analysis, aiding in the early identification of deteriorating conditions and improving long-term treatment planning. By integrating IoT technology, the system enhances healthcare accessibility and ensures uninterrupted monitoring, making it a valuable tool in both hospital-based and home-care settings.

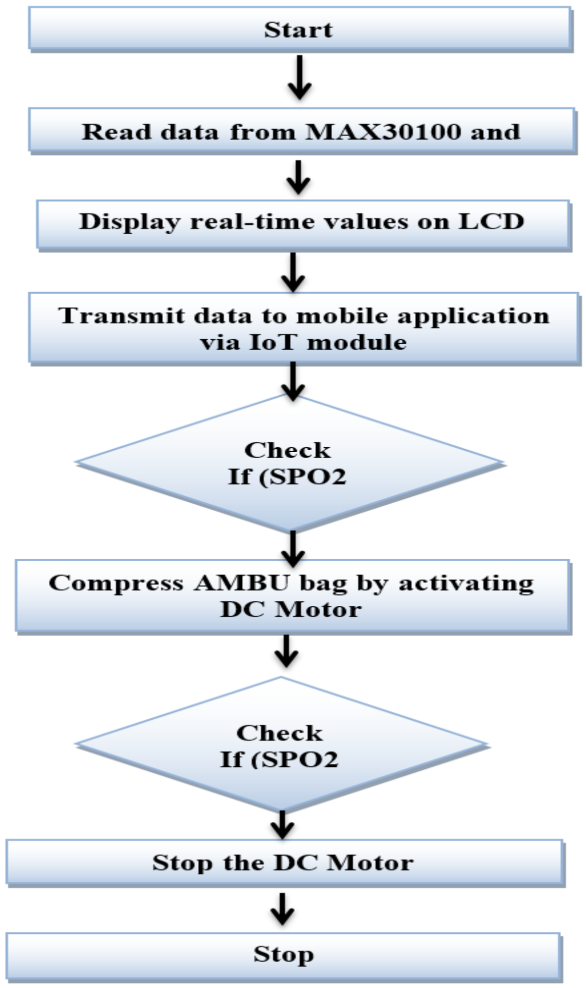

Figure 2 Flowchart

To further improve usability, the system is lightweight and portable, making it highly suitable for use in ambulances, emergency care units, and field hospitals. Its real-time data transmission and analysis capabilities provide an added advantage in telemedicine applications, enabling doctors to monitor multiple patients remotely without the need for physical bedside visits. This feature is especially crucial in resource-limited settings, where access to specialized respiratory care is often restricted. The integration of automated alert mechanisms ensures that clinicians receive immediate notifications in case of deteriorating patient conditions, preventing delays in treatment and enhancing patient safety.

4. Results and Discussion

The proposed automated respiratory monitoring and ventilation system was evaluated for its accuracy, efficiency, and feasibility in providing continuous monitoring and emergency ventilation support. The comparative analysis of cost and weight with commercially available ventilators highlights the system's advantages in affordability and portability. The following tables present a detailed comparison of cost and weight with other ventilator brands. Refer Table 1 to 3.

Table 1 Cost Comparison of the Proposed Ventilator with Commercial Ventilators

Ventilator Model	Cost (USD)	Availability
Proposed System	$250	High
Philips Respironics Trilogy 100	$6,500	Moderate
Hamilton-T1	$15,000	Low
Medtronic Puritan Bennett 980	$20,000	Low

Table 2 Weight Comparison of the Proposed Ventilator with Commercial Ventilators

Ventilator Model	Weight (Kg)	Portability
Proposed System	2.5	High
Philips Respironics Trilogy 100	5.6	Moderate
Hamilton-T1	6.7	Moderate
Medtronic Puritan Bennett 980	12.5	Low

Table 3 Performance Comparison of the Proposed Ventilator with Commercial Ventilators

Ventilator Model	SpO_2 Monitoring Accuracy	Response Time (ms)
Proposed System	±1%	High
Philips Respironics Trilogy 100	±2%	Moderate
Hamilton-T1	±2%	Moderate
Medtronic Puritan Bennett 980	±1%	Low

These comparisons indicate that the proposed ventilator system offers a lightweight and cost-effective solution for emergency and home-based respiratory care. While traditional ventilators provide advanced functionalities, their high cost and weight limit their accessibility in low-resource settings. The proposed system bridges this gap by providing an affordable, portable, and effective respiratory support mechanism, particularly for patients requiring non-invasive ventilation and continuous monitoring. Future enhancements, including an improved power management system and adaptive ventilation algorithms, will further optimize the system's efficiency and usability across diverse healthcare applications.

5. Future Scope

The future scope of this research aims to enhance the efficiency and adaptability of the automated respiratory monitoring system by incorporating advanced biosensors to enable a more comprehensive assessment of patient health. The integration of additional physiological parameters, such as respiratory rate, blood pressure, and electrocardiogram (ECG) monitoring, will provide a multi-faceted approach to early disease detection and intervention. To ensure uninterrupted functionality, future iterations will focus on optimizing power management by incorporating an external battery backup, making the system more reliable in emergency and resource-limited settings. Furthermore, advancements in IoT security protocols will be explored to enhance data encryption and secure cloud-based storage, ensuring the confidentiality and integrity of patient health records. Adaptive control mechanisms for the AMBU bag compression system will be developed to provide personalized ventilation support based on real-time patient needs, improving therapeutic effectiveness. Additionally, seamless interoperability with hospital management systems and telemedicine platforms will be prioritized to enhance accessibility and streamline patient care. Through these advancements, the proposed system has the potential to evolve into a highly scalable and intelligent respiratory monitoring solution, suitable for both clinical and homecare applications.

Conclusion

In conclusion, this study presents a comprehensive and automated respiratory monitoring system that integrates biomedical sensors, microcontroller-based control, and IoT-enabled remote access to enhance patient care. The implementation of the MAX30100 pulse oximeter and DHT11 temperature sensor ensures precise and continuous tracking of critical physiological parameters, facilitating early detection of respiratory distress. The incorporation of a microcontroller-driven AMBU bag compression mechanism enables timely and automated ventilation support, minimizing reliance on manual intervention in emergency scenarios. Additionally, the IoT module allows seamless real-time data transmission to healthcare professionals, ensuring continuous monitoring and prompt medical response even in remote or resource-limited settings. The system significantly improves patient safety, clinical decision-making, and healthcare accessibility by providing a scalable and efficient respiratory support solution.

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