Low-cost Portable Ventilator Design for Underdeveloped Regions

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Abstract—COVID-19 pandemic has caused a significant shortage of ventilators. Roughly over one-sixth of the patients for COVID-19 need ventilators for treatment and the ventilator storage cannot meet the demand of hundreds of thousands of infected cases. This shortage is particularly severe in developing countries, where limited resources restrict industrial output capabilities. Existing high-end ventilators are too costly while low-cost ones have insufficiently functionalities. In this research, we want to resolve this issue by developing a low-cost (less than $300) portable ventilator with more comprehensive capabilities for use in developing countries. Using a Bag Valve Mask (BVM) as the foundation, customized biometric sensors and gas processing technologies are integrated to enhance functionality while maintaining cost-effectiveness and reliability. A Manual airbag is pushed upon by a stepper-driven leadscREW, which delivers the necessary quantity of air while controlling the volume. A low-cost ECG sensor and a blood oxygen sensor are combined to form a patient biometrics anomaly detection system. The prototype functionality is verified experimentally. The on-going work involves the development of more advanced algorithms for accurate biometrics anomalously detection, which will allow alerts to be sent wirelessly to doctors. With the affordable full-functional prototype, the low-cost ventilator design can become more widely available for practical applications, allowing countries to better prepare for future pandemics.

Index Terms—Ventilator, Biomechatronics, Design, Affordability

I. INTRODUCTION

In modern clinical medicine, ventilators are effective means to replace the function of voluntary ventilation artificially. It has been widely used in various causes of respiratory failure, anesthesia, and respiratory management during major surgery, respiratory support treatment, and emergency resuscitation. Due to its vital functions in clinical medicine, the ventilator occupies a very important position in modern medicine.

Ventilators have been widely used in modern clinical medicine. They are effective in various causes of respiratory failure, anesthesia, and respiratory management during major surgery, respiratory support treatment, and emergency resuscitation and plays a critical role in modern medicine. Researchers are also actively working on new technology to improve the functionalities of high-end ventilators. Recent developments include: reducing the damage to lungs [1] or adding a multi-function online monitoring system[2].

A ventilator is a vital piece of medical equipment, particularly during the COVID-19 pandemic, as it may prevent and cure respiratory failure, reduce consequences, and enable COVID-19 patients to have a better sleep quality [3]. Non-invasive pressure support is also beneficial since it can help reduce lung damage, specifically volubarotrauma and atelectotrauma, in the short term. Positive airway pressure (CPAP) and nasal intermittent positive pressure ventilation (NIPPV) have similar physiologic properties: they both promote the production and conservation of surfactant while preserving functional residual capacity, recruitment, and decreasing upper airway collapse[4].

The pandemic of COVID-19 significantly increases the need for ventilator therapy. At the beginning of the pandemic in 2020, more than 2000 people in the United States had to share one ventilator in the hospital with the existing storage. This means a shortage would arise if over 6 people out of 2000 got infected at the same time, a ventilator shortage would occur. It turned out the infection rate is much higher than 0.3 percent and many new ventilators are being produced to alleviate the situation. The number of ventilators in United States is now estimated between 60,000 and 160,000, depending on whether or not those with just limited functionality are included[5]. As a result, the national strategic reserve of ventilators is limited and insufficient to cover the predicted shortfall. Moreover, for less industrialized third-world countries, the shortage is even more server and the capability to produce new ventilators are also limited. As a result, patients have more limited access to ventilators [6]. The main reasons for such phenomenon are simple: existing ventilators are either too expensive or inadequate in terms of functionality for low-cost designs. High-end ventilators typically cost more than ten thousand USD per installment and cannot be quickly produced. The supplement of ventilators is limited, which also affects the supply chain. Because of the widespread of the virus, the export of medical equipment, including ventilators, has been halted altogether. The situation has deteriorated to such an alarming degree that as many as 54 nations have suspended the export of medical-related products, including ventilators. Therefore, the key to solving the problem is to design a relatively cheap product that can be mass-produced in a short period and can replace the high-end ventilators to some extent.

The lower-end Bag Valve Mask (BVM) requires time-consuming manual pumping with a high risk of infection and secondary injury to the patient. Therefore, BVM is conventionally used only for emergency short-term ventilation. To resolve this issue, researchers at MIT have developed an
automated BVM-based ventilator[7]. The motor and control system of low-cost portable ventilators is based on the human action of squeezing the exhalation bladder by hand, and the gas delivery is accomplished through the motor and control system[8]. It reciprocates in cycles to accomplish the goal of aiding breathing. However, the functionalities for patient biometric sensing and doctor alarming are still missing from many previous designs. For COVID-19 patients, monitoring of biometrics and adjust the ventilator flow and pressure parameters correspondingly is very important. This function provides quick feedback on the patient’s condition before the optimum period for therapy is lost and the illness progresses to a more severe stage of the disease.

Therefore, a low-cost portable ventilator can be utilized to augment the ventilator gap in third-world countries, assisting in treating patients with COVID-19. In this paper, we developed a ventilator with the following characteristics:

- Controlled cost within $300 per person
- Equipped with digital control system and patient monitoring system
- Equipped with adjustable oxygen units
- Able to send alarm when the patient’s vital signs are abnormal

II. SYSTEM-LEVEL DESIGN

A. Functional Requirements and Specifications

In this study, we present a solution intended to meet the demands of third-world countries to treat patients affected by the COVID-19 outbreak by providing short-term non-open trachea oxygen and sanitizing exhaled air. This mechanical design achieves the fundamental functionality of automatic air supply, which is identical to that achieved in prior systems. The design also incorporates the following additional features:

- Electrocardiogram and oxygen concentration sensors, as well as a wireless alert system.
- The use of supplemental oxygen delivered through a three-way valve from portable canisters.

As shown in Figure 1, the design has four primary subsystems: the energy supply system, the oxygen supply system, the monitoring and alarming systems (drawn separately), and the central control system. This portable ventilator’s energy supply system is supplied by either a lithium battery or a wall-plug AC adapter; the former is utilized to meet portability needs, while the latter is meant for long-term (about one week) use. It is composed of an airbag that may be compressed by a stepper motor, connected to oxygen cylinders and air filters by a hose. Purification will be provided for both the air that patients breathe in and out, safeguarding both the patients and those around them. The alarm system is also connected to several sensors that monitor the patient’s blood pressure and oxygen levels, which can be used to display a visual representation of the patient’s physical status. With the MAX30102 model, patients’ heart rates and oxygen saturation can be easily monitored, and additional sensors can collect data from both the patients and the ventilator, allowing for more accessible data analysis and, ultimately, better patient outcomes. All of the data will be sent through the control system, programmed using two Arduino microcontroller boards. Because of the restricted functionality and power of a single Arduino motherboard, we chose to isolate the control of the stepper motor from the treatment of data—two motherboards substantially boost the system’s reliability and provide for greater flexibility. Through the use of a blue tooth model, the data acquired by the ventilator will be communicated to a computer and a smartphone, where it may be utilized to notify patients’ families and draw an electrocardiogram.

The device is designed based on the basic statistics of a typical adult with a lung capacity ranging between 5500 and 6000ml. This product is planned to be in use for three to seven days and to be able to sustain patients when hospital beds are in short supply. The manufacturing cost is expected to be kept under 800 Chinese yuan. The portable ventilator can be utilized as a supplement to the ventilator gap for a short amount of time at a reasonable cost to assist patients with COVID-19 who are suffering from respiratory failure. The initial prototype, which includes a gas processing system and biometric sensors, is created in Solidworks. After that, a test model is constructed from standard components that can be obtained on the internet.

![Fig. 1. Five primary modules of system design—energy supply, gas supply, electronic control, sensors, and alarms](image-url)

B. Energy Supply System

A 24V lithium battery or a wall-plug adapter DC adapter can be used to power the ventilator in either mode. The Arduino motherboard and the stepper motor are the two structures that use the majority of energy. In the entire operation, a 15-watt stepping motor and a 5-watt Arduino board will consume a combined total of 20-watts of electricity. This system may
be operated for around 7.5 hours on one lithium battery with a capacity of 60,000mAh and a volume of 1400cm³. When patients are transported to the hospital or are in an emergency scenario, this design can completely satisfy their demands. In addition, the needed input current has low voltages of 12V, which means there is no possibility of leaking, resulting in secondary harm to the system. Overall, the power structure for the ventilator is portable, safe, and stable.

C. Oxygen Supply System

The action of people using first aid airbags is taken into consideration when designing the oxygen supply system. The airbag is squeezed by a stepping motor coupled to a lead screw over a predetermined duration. There are two air input ports located at the bottom of the airbag. The larger of the two is for regular air, and the smaller is for pure oxygen, as seen below. It is feasible for the user to manage the incoming air quality and oxygen proportion by incorporating a filter and a controlled pressure valve. The exhaled air will exit the respirator mask through a breach in the joint created by a monomial valve. Exhaled air can be purified and filtered by designing a shell that surrounds the joint where the exhaled air comes out and connecting one end to a filtration cloth. An FDM printer can be used to 3D print the part at a reasonable cost. Overall, the entire oxygen delivery system is designed to replicate human activity and may meet a variety of purposes, including supplying oxygen to the patient, adjusting the oxygen concentration, and filtering the air that is inhaled and exhaled.

D. Monitor and Alarm System

The currently available low-cost ventilator is not fitted with a monitor or an alert system. It is inconvenient since patients’ status and vital signs cannot be determined, resulting in the possibility of secondary injury to patients. We can monitor the heart rate, blood oxygen level and draw an electrocardiogram with this design. The heart rate and blood oxygen level can be displayed on an LED screen and a smartphone application connected through Bluetooth to the ventilator. There are no cuts required for collecting data because all of it is done through the use of sensors attached to patients’ bodies. The second benefit of its design is that it decreases the possibility of infection. The smartphone application will sound an alarm and prompt the user to contact an ambulance or other emergency medical assistance if one of their vital signs falls below a certain threshold. At the output side of the ventilator, a gas flow meter is incorporated into the hose that connects to the patient’s breathing mask. It measures the volume of gas squeezed out by one cycle of the stepper motor. Using this, the ventilator design in this paper can adjust the volume of gas output by the breathing airbag according to the patient’s lung volume (0-4000 ml) to reduce damage to the patient’s lungs.

Figure 2(a) shows a companion application for Android phones developed using MIT App Inventor. As shown on
Figure 4 and works appropriately. In this ventilator model, the air filter is not represented, but it can be easily installed on the side of the respiratory mask, where the patient’s exhaled air is collected.

Figure 5 shows an ECG diagram collected by the AD8232 module with three patches located in the stomach, left chest, and right chest. From Figure 5, it is easy to interpret vital signs such as voltage, P-wave, and timing intervals. Such information could be helpful for the doctor to determine patients’ condition for further treatment.

IV. Future Work
The ongoing tasks include optimizing signal processing in order to process biometric anomalies better. The current algorithm for anomalies in heart rate is adapted from the anomaly detection that comes with the sensor. In the medical field, doctors may have different criteria to judge it. Therefore, this algorithm should be optimized again before it is put into application. It is also intended to do further research on mobility and battery operation. We believe that our low-cost open-source design can assist developing nations in overcoming their present difficulties and being better prepared for potential pandemic crises in the future.

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