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Development of a Low Cost and Portable Ventilator Prototype

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Abstract: A ventilator is one of the most important pieces of equipment every hospital should have. In practice, a ventilator is a bedside machine that takes over the breathing process of a patient suffering from respiratory failure. A ventilator works by pushing breathable air into and out of a patient's lung mechanically. This paper outlines the development of a portable ventilator prototype that is substantially less expensive and can be developed in the event of a ventilator scarcity during a pandemic or disaster. The Artificial Manual Breathing Unit (AMBU) bag is used in the development of this prototype for automatic assisted ventilation. This study found the developed system performed better than the manual method in delivery of breaths with high consistency of 18.6 ± 1.45 bpm. This system can also be run on batteries for more than four hours. This prototype costs not more than RM200 lower than those in the market. It is also energy-efficient and portable, making it a feasible alternative for mass casualties and resource-limited scenarios. The future of this work includes the addition of assistive control mode for a more reliable and effective breath delivery.

Keywords: Ventilator, AMBU, Prototype

1. Introduction

In both industrialized and developing countries, respiratory illnesses and injury-induced respiratory failure are a major public health issue. Many of these health issues are caused by disorders that are exacerbated by air pollution, smoking, and biomass burning as a source of energy. This could result in the spread of lung disorders like asthma, chronic obstructive pulmonary disease, and other chronic respiratory conditions, as well as catastrophic respiratory system problems. People presently suffer a slew of respiratory problems that might stem from a variety of causes, but they all pose a serious threat to public health [1]. Consider the Coronavirus disease outbreak (COVID-19), which was declared a pandemic in March 2020. COVID-19 is a new coronavirus that causes an infectious disease. The infected patient would develop a few mild symptoms such as fever, dry cough and tiredness. However, after a few days the mild symptoms could turn into a severe symptom, which is a shortness of breath or clinically known as dyspnea. The equipment typically used to treat patient with breathing failure diseases is a ventilator.

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Ventilators are often referred to as "breathing machines" or "life support." They are machines that breathe for the patient when a patient is unable to take in air on his/her own. When a person is placed on a ventilator, a tube is inserted into the windpipe, either through the mouth, or through a hole in the throat called a tracheostomy. This tube is connected to a machine that pumps air into their lungs. On the other hand, ventilators are commonly used to breath for the patients during surgery and during short-term treatment of illnesses such that dyspnea or pneumonia. Ventilation allows the body to rest while it recovers from injury of infection. Ventilators are one of the most popular medical tools, and they're used to keep intubated patients or those with heart failure getting enough oxygen [2]. There are numerous ventilation equipment on the market right now. Positive pressure, negative pressure, and high-frequency ventilators are the three types that can be classified based on how they work [2]. However, this device is expensive, and hospitals only have a limited supply of it.

However, when there is a lack of readiness for mass casualty events such as influenza pandemics, natural catastrophes, and huge toxic chemical releases, it could be a significant issue [3]. This is due to an increase in the number of patients that need to be treated right away. In wealthy countries, the costs of stockpiling and deploying state-of-the-art mechanical ventilators for mass casualty situations are prohibitive [3]. In a worst-case pandemic, the United States would require up to 742,500 ventilators, according to President Bush's national preparation plan released in November 2005. When compared to the 100,000 currently in use, the system clearly falls short [3]. For example, during the latest pandemic epidemic in 2019, health care personnel highlighted concerns about an impending scarcity of ventilators to treat patients. Given the scarcity of stocked ventilators and their current high cost, there is a need for the creation of a low-cost portable ventilator that can be mass-produced on demand. As a result, this ventilator prototype system is a cutting-edge, cost-effective, and fully functional hospital ventilator.

2. Methods

2.1 Block Diagram

Figure 1 shows the schematic block diagram of the system operation. This operation started from the microcontroller which is the main component in this system as a set of coding was uploaded into this component. From the microcontroller, the H-bridge that was located in the L298 motor driver was used to control a DC motor from Arduino to compress and release the AMBU bag. This mechanism gives breaths to the patient.

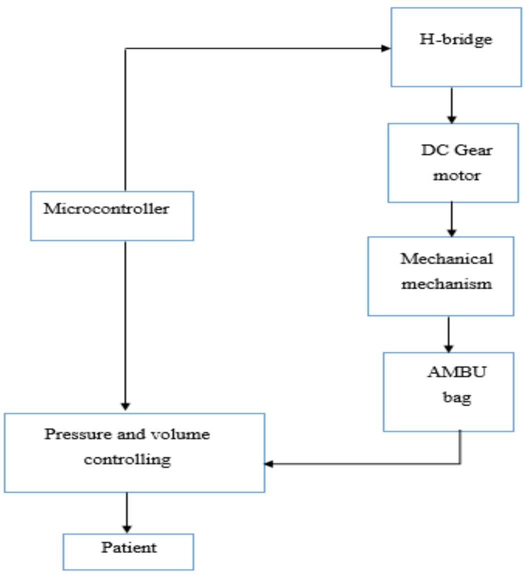

Figure 1: System block diagram

2.2 Flow Chart

In this project, mandatory control mode is used by default. The flow of the breath delivery system is shown in Figure 2. The breath delivered to the patient is based on the equal time delay by using an internal timer at the controller. The time delay set depends on the breath rate prescribed by the doctor. The breath delivered is set to 60cmH2O(centimeter of water because of the pressure limiting valve at the AMBU bag. This value also the found to be the maximum breath pressure needed for an adult patient.

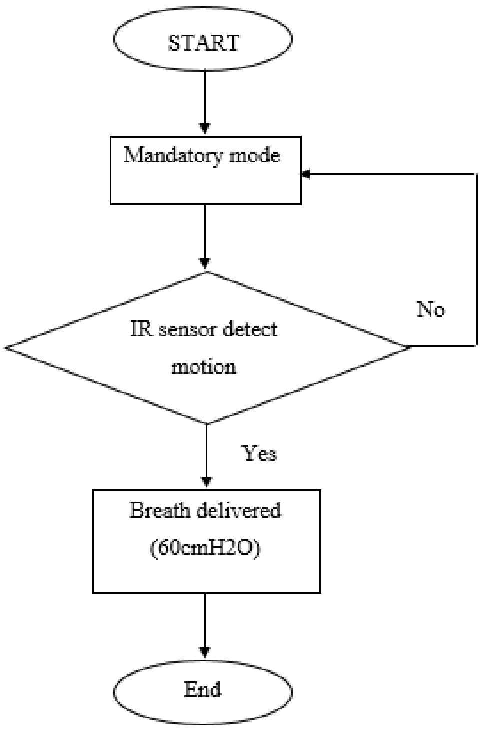

Figure 2: System of flow chart

3. Results and Discussion

3.1 Circuit Simulation and Development

The circuit schematic shown in Figure 3 is simulated using Proteus 8 Professional software prior to circuit development. This simulation is performed to confirm that all components in the circuit are properly connected and there are no short circuits or faults in the designed circuit. The Arduino UNO, infrared sensor module (SN-IR-MOD), and L298 motor driver are the major components of this circuit. The DCmotor is driven by the L298 motor driver, while the infrared sensors (indicated as IR1 and IR2) are used for detection of the inflation and deflation of the AMBU bag. The AMBU bag inflates when rotated clockwise, and deflates when rotated counterclockwise. Table 1 shows the voltage differences measured (in practice) at the IR sensors during the deflation and inflation of the AMBU bag. Figure 4 shows a diagram of the completed prototype. Also shown in the diagram is the artificial lung used in the testing of the prototype.

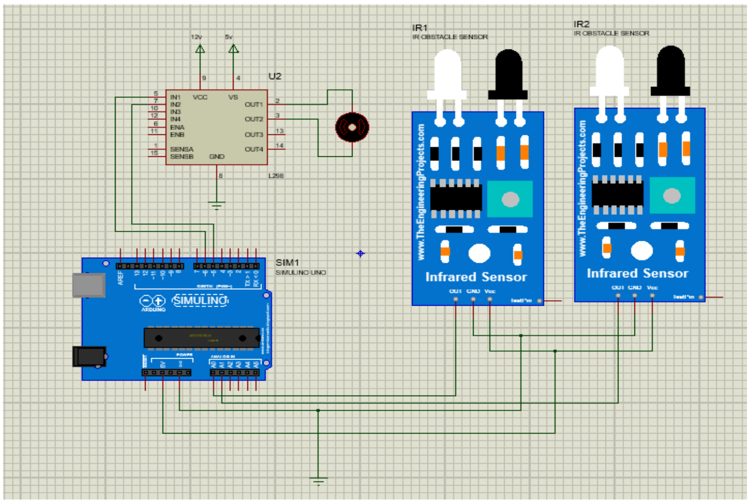

Figure 3: Circuit diagram and simulation using Proteus 8 software

Table 1: IR sensors measurement for different AMBU bag status

AMBU Bag	DC Motor	IR Sensors Voltage (V)	
		IR1	IR2
Inflate	Clockwise	4.66	0.37
Deflate	Anti-clockwise	0.36	3.53

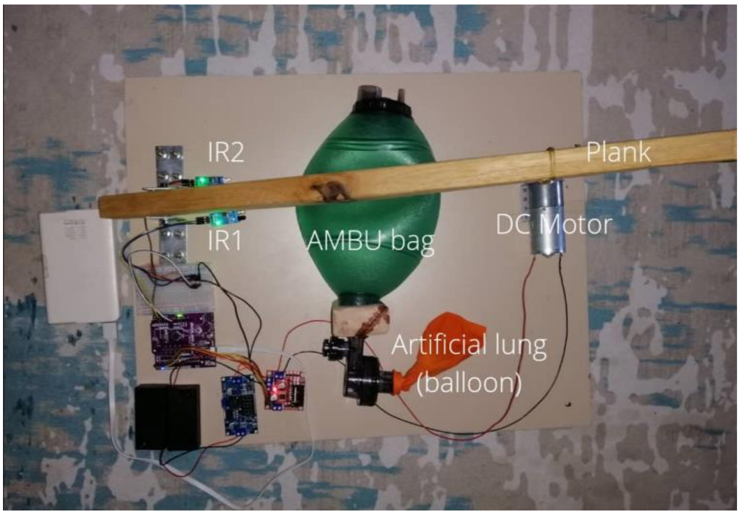

Figure 4: Completed ventilator prototype

3.2 Battery Capacity Test

The prototype's battery life time was tested by running the ventilator on a phantom lung until the battery completely depleted for system operation. In this study, the test was timed for eight hours for the battery to drain as shown in Figure 5. The line graph shows its diminishing pattern, wherein the battery capacity drops with the operation time. The energy stored dropped to 50% of its total capacity by the sixth hour of the test, before totally it was completely depleted between the seventh and eighth hours.

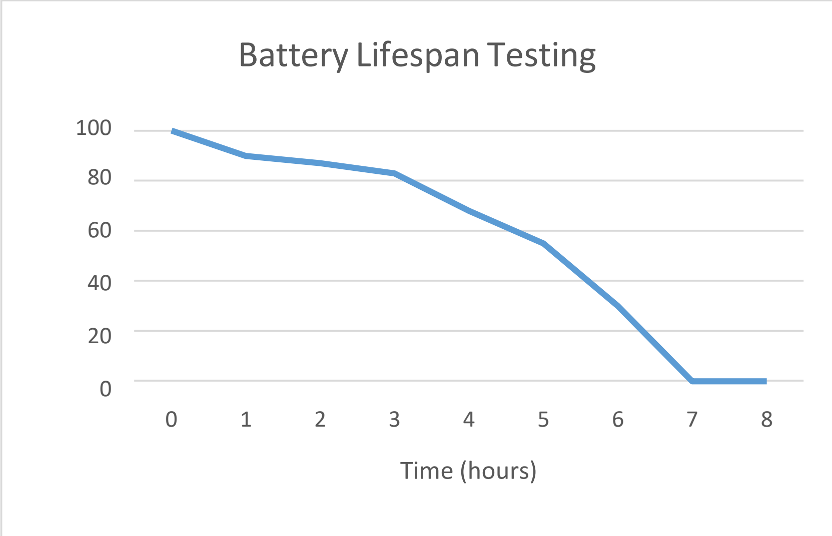

Figure 5: Battery capacity (%) versus operating time (hours)

3.3 Air Compressions Testing

The purpose of this test is to compare the output from manual and chained plank mechanism compression. Since an adult's normal breathing rate is between 12 and 20 breaths per minute, thegoal of this test is to investigate which approach is able to maintain between 12 and 20 compressions (or analogous to breaths)throughout a period of 10 minutes. The results (in number of compressions delivered) from manual and automatic technique (of the developed system) are compared and shown in Figure 6. To account for inconsistency in the developed system performance (due to factors such as battery performance), the experiment was repeated three times.

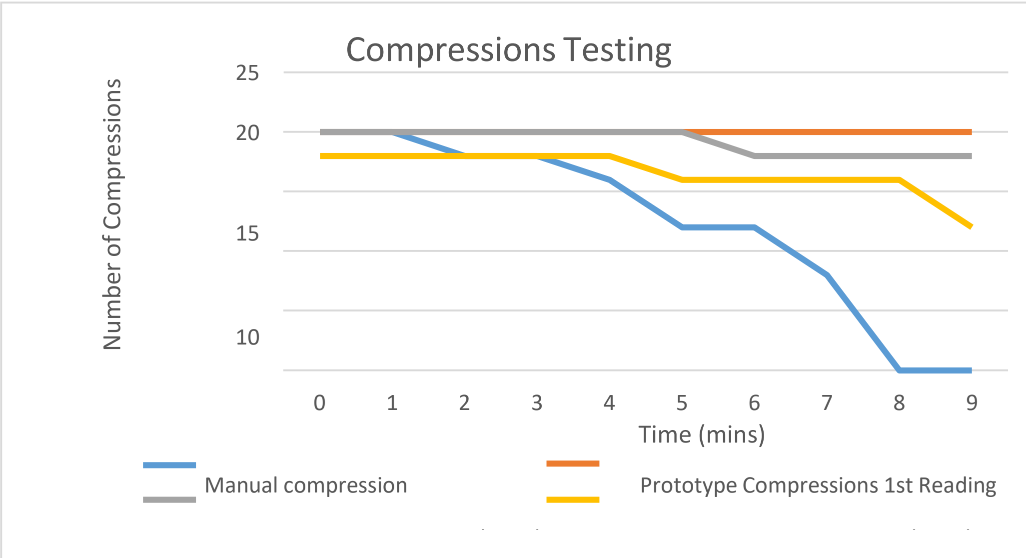

Figure 6: Number of compressions versus time

The manual compression is done by pumping the AMBU bag for 10 minutes using self-energy, whereas the prototype compression is done with the system's chained plank mechanism. Based on Figure 6, the manual compression approach shows a diminishing (in breaths delivered) tendency. Furthermore, this technique was unable to maintain the required minimum compression rate of 12 compressions per minute. Even though the prototype compression shows a declining pattern, it does not go below the minimum level of compressionrequired. This system manages to keep the compressions for the entire ten minutes of testing operation. The results from the three consecutive experiments also show the system has well repetitively. After 10-minute, the compression rate was found to remain constant at10-12bpm. To investigate consistency in the performance of the breath delivery systems.

The mean and standard deviation (μ ± σ) of fluctuations arecalculated using formula shown in Eq. 1 and 2, respectively. The results are tabulated in Table 2.

$$\text{Mean, } \mu = \frac{\Sigma xi}{x} \quad \text{Eq. 1}$$

$$\text{Standard deviation, } \sigma = \sqrt{\frac{(xi-\mu)^2}{N}} \quad \text{Eq. 2}$$

Table 2: Mean and standard deviation (μ ± σ) in the delivered breaths per minute

Method	Breaths per minute (bpm)
Manual compression	11.6 ± 4.82
Mechanical compression (first attempt)	20 ± 0
Mechanical compression (second attempt)	19.2 ± 1.26
Mechanical compression (third attempt)	16.6 ± 3.85

The overall mean and standard deviation from the three readings (for mechanical compression) shown in Table 2 are calculated as 18.6 ± 1.45 bpm. Meanwhile the relative difference, σ, in the number of delivered compressions, N_{del}, from the required value of N_{ref}= 20 bpm (i.e. used as reference) is calculated using Eq. 3 as 42 % and 10 %, using results from manual and from average mechanical compression techniques, respectively.

$$\text{Relative difference, } \sigma = \left(\frac{N_{del}-N_{ref}}{N_{ref}}\right) \quad \text{Eq. 3}$$

In this study, the mean for the manual compression is found to be 11.6 bpm while overall mean compressions produced by the developed prototype is given by 18.6 bpm. There is also higher consistency of 1.45 bpm from the automated system as compared to 4.82 bpm from the manual process. This produced a lower percent error of 10 % using the developed prototype while 42 % was observed for the manual compression. This suggests higher consistency in the performance of the prototype.

3.4 Comparison with Existing System

Table 3 shows a study made comparing the functionality and cost of the developed prototype as compared to those offered in the market. Based on the findings, the total cost used in developing the current prototype is significantly lower than that in the market. This is, however, at the price of having inferior functionality and features. It is expected that its features can be enhanced with the inclusion of auto mode or real-time monitoring system, and to reduce in its size.

Table 3: A comparison of product costing and features with that in the market.

Product	Features	Price (RM)
Puritan Bennett™ 980 Ventilator Series	• Touch screen that is both intuitive and highly configurable • To better visibility, graphs can be resized and extended to full screen. • The screen can be paused and review the last 60 seconds of patient data by pressing the pause button.	RM135 000.00
Servo-I Ventilator Getinge	• It also includes a number of tools that can assist you in stabilizing your patient and weaning them off the ventilator. • Auto mode assists your patients in transitioning to spontaneous breathing with less intervention from staff.	RM2 852 887.50
Maquet Servo-u™* Ventilator	• When an alarm is triggered, the frame illuminates, and this visual signal is visible from any angle. • On-screen checklists aid in the management of active alarms and the avoidance of unwanted alarms. • From the pre-use check to the initial parameter setting and throughout the treatment, Servo-u provides helpful guidance.	RM1 902 925.00
Drager Evita™* Infinity™* V500 Ventilator	• On-invasive ventilation is available in all modes and for all patient groups. • O2-Therapy allows for a constant flow of oxygen. • Flexible screen configuration: each patient can have up to six different views depending on their therapy. • All patient data, alarms, and trends are kept in full record.	RM6 339 750.00
Hamilton g5 ventilator	• Automated regulation of the patient's breathing and oxygenation with INTELLiVENT®-ASV® • Real-time patient synchronization with IntelliSync+ P/V Tool Pro for lung assessment and recruitment • Trans pulmonary pressure measurement • High flow oxygen therapy	RM8 664 325.00
Ventilator prototype	• Comes with portability features. • Offer a ventilator mandatory mode. • Able to supply until 60cmH2O air pressure.	RM 150.00

4. Conclusion

In this study, a prototype featuring energy-efficient, portable, and low-cost breath delivery system was developed. This prototype can be operated by connecting the Arduino to the power supply and switching ON the batteries. This study used IR sensing technology for detection of inflation/deflation of AMBU bag. Based on the obtained signals, the mechanical mechanism would automatically trigger the AMBU bag to inflate hence producing the air needs by the lung. This provides a constant air flow to the artificial lung. This work found a comparatively higher consistency in the breath delivered of 18.6 ± 1.45 bpm and lower performance discrepancy of 10 % using the developed system as compared to that of manual method. Furthermore, the price incurred on making this ventilator prototype is just below RM200. The low price is result of the low end off-the-shelf items and also the sensors used can also be found. In the future, a function, as well as a PEEP valve, a humidity exchanger, and a blow-off valve, can be added to further enhance the performance of the developed system. Last but not least, the wooden cutting board should be replaced with an acrylic board for the casing. This is because the wooden board is much more heavily compared to the acrylic board. An acrylic board offer much more lighter features and compact that is more suitable for the portability of this project.

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