Designing an Electro-Mechanical Ventilator Based on Double CAM Integration Mechanism

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***Abstract*—This paper proposes a simplified structure of microcontroller based mechanical ventilator integrated with a Bag-Valve-Musk (BVM) ventilation mechanism. Here, an Ambu bag is operated with computer-aided manufacturing (CAM) arm that is commanded via a microcontroller and manual switches by sending a control signal to the mechanical system and according to this control signal, the mechanical computer-aided manufacturing (CAM) arm simultaneously compresses and decompresses the Ambu bag. It is a self-inflating bag and like a one-way valve around its inlet and outlet corner. By compressing the Ambu bag it delivers air and by relaxing, it takes air from the environment through a mechanical scavenger. The control signals are designed with three modes named adult mode, pediatric mode, and child mode based on the respiratory rate. The device is in assist controlled mode by dint of fixing the tidal volume for all unique control signals. The control signal is visualized by a platform known as the BIOPAC student's lab system. The proposed device is portable, compact, low weight, and efficient performable. It can be supplied around the rural area hospitals for immediate medication with cost efficiency and risk avoidance. Anyone can operate it as no need to study or training of ventilation rules like ICU ventilator. The proposed system is safe, riskless, and repairable. The angle, volume, and respiratory measurement have found 95%, 92%, and 90% accuracy respectively. By applying this portable ventilator system immediate attention can be taken up in rural or general hospitals and in ambulances.**

Keywords—Ambu bag, Automation, computer-aided manufacturing arm, positive pressure ventilation, Portable, Emergency ventilation system

I. Introduction

In this era of modern science, the uses of microcontrollers are increasing day by day. Integrating with it the automation systems are improving. A manual resuscitator generally known as Bag-valve-musk (BVM) ventilator is used in the mechanical ventilating system. Manual compression, as well as relaxation of an Ambu bag, is inaccurate and painful for the operator with an unknown volume of air. Reducing this specific problem an automation system is necessary for well delivery of air for the person who is unable of taking a breath. Ambu stands for Artificial Manual Breathing Unit. It was invented in 1956 by German engineer doctor Holger Hesse and his partners. In 1559 an Italian professor of anatomy named Matteo Realdo Colombo recounted a method called tracheotomy's method [1].

For attainment a better output, an approximate mechanism is maintained for controlling Ambu bag. In this paper, a specific mechanism is used to get the required output from the system. A normal adult (18 years aged or more) person generally takes 12-20 breath within a minute where a child (1- 12 month aged) has 30-60.

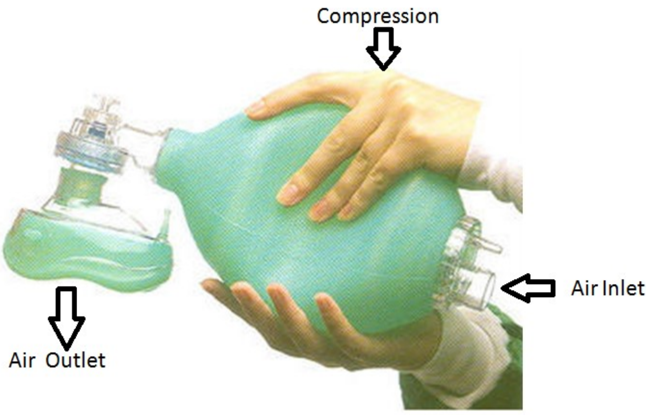

Fig. 1. Manual operation of the Ambu bag system.

It is clear that the respiratory rate of a child is faster than an adult. Out of them, pediatric (6-11 years aged) persons have the respiratory rate (RR) of 18-25 per minute. Authors in [2] describe the detection and monitor of a metabolite of pneumonia at the early stage. A silicon Ambu bag is chosen for its auto relaxation property. This property takes zero energy for relaxation and thus automation system makes flexible. At an emergency condition in ambulance sometimes need 90 percent or more oxygen for the patient recovery. So portability and low power consumption is a great fact for patient care.

With the rapid growth of medical technology, the configuration architecture of the ventilators is becoming complex day by day due to the integration of mechanical, electrical, electronic, and computational technologies [3]. Authors in [4] describe a roller-chain method where this chain compression makes a force on an Ambu bag. This method is acceptable to some drawbacks. There is some possibility of breaking chain thus be dangerous in an emergency condition and need huge torque to compress it. In paper [4], another mechanism named Cam-arm mechanism (CAM) is shown. The cam-arm mechanism is better than the roller chain mechanism on account of its noise reduction property. Our prototype is designed on the basis of two handmade CAM-arm functions that use optimal torque with noise reduction, low power consumption, portability augmentation, and better output. Lung-protective ventilation is treated as a simple supportive therapy and also as a prophylactic therapy to attenuate patient self-inflicted lung injury [5].

The paper is organized as follows: Section II describes the materials and methodology. This section describes the framework of the proposed method; the existing system, proposed system, CAM arm mechanism, BVM mechanism, corresponding mathematical formulation, and circuit diagram. Section III gives hardware implementation and its relative advantages and disadvantages. Section IV gives the results and discussion of the proposed system. Finally, section V concludes our paper with some future directions.

II. Materials and Methodology

A. Flowchart of the Proposed Research

The basic framework of the proposed research work is shown in Fig. 2.

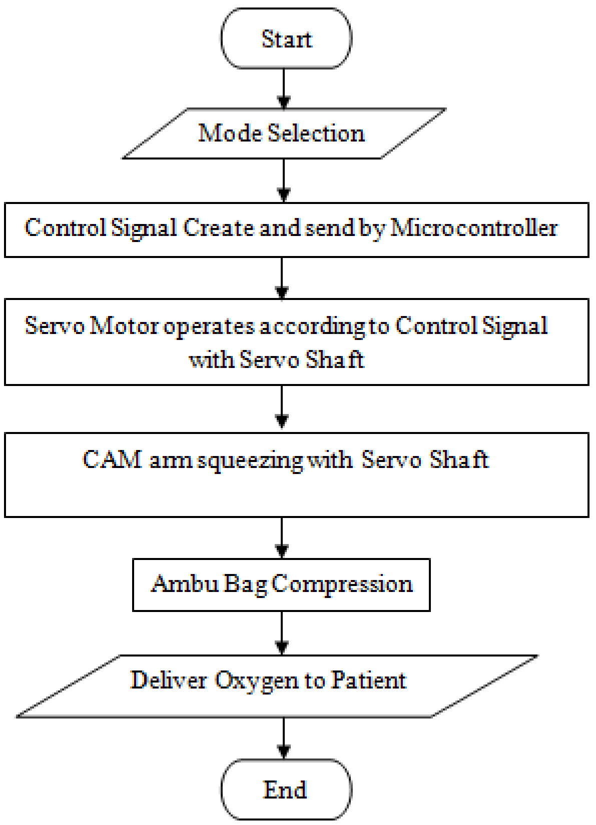

Fig. 2. Basic flowchart of the proposed work. The flowchart represents three modes at a time (Adult mode, pediatric mode, and child mode).

B. Existing System

There are several existing systems of operating an Ambu bag. Such as Ruler chain mechanism, CAM mechanism, Rack and pinion mechanism, Lead screw Mechanism. They have some advantages and disadvantages. Another existing ventilator system is integrated with the vocal alarming system to reduce noise that generates from ventilators in the hospital [6]. Ruler chain mechanism is preferred in previous for its availability and high torque gain with DC motor. When it operates, noise generates that can cause sound pollution in the care environment. Tele-controlling mechanism exists and integrated with the system [7, 8]. After that, another mechanism preferred called CAM mechanism eradicates the noise or additional sound. Actually, this mechanism does not generate any noise like ruler chain mechanism. Rack and Pinion mechanism makes the platform of gear for more precise controlling. Lead screw mechanism uses a threaded screw to operate a mechanical arm with a nut that compresses and relax the Ambu bag simultaneously. Authors in [9] show the hyperbaric oxygen therapy using mechanical ventilator where the pressure is proportional to volume.

C. Proposed System

Our proposed system is based on CAM principle having some additional feature of controlling precisely with portability, battery operated, reduced size and noise removal. Several modes selected for control operation such as child mode, pediatric mode, and adult mode. These modes are selected according to the lung capacity and breath-rate of the subject as well as inspiration and expiration (I:E) ratio. All of these parameters are generally dependent on the age of the subject. The automation requires a microcontroller, some mechanical switches, and two servos. Servos are positioned face to face oppositely with the 180-degree angle. The shafts of the motor are attached with a mechanical pulley that rotates according to motor direction. A nonflexible cot wire connects one arm and one pulley and same to the second one. When the motor rotates, the torque creates tension in the cot wire through the pulley that results in pulling a mechanical arm to compress an Ambu bag.

D. Computer-Aided Manufacturing Arm Mechanism

A CAM (Computer-Aided Manufacturing) arm is a rotating or sliding piece in a mechanical linkage that is used especially to convert rotary motion into linear motion which is shown in Fig. 3. The main reason for selecting a cam arm is the servo system as it has a high torque of approximately 15 kg-centimeters. The arm is nonflexible, hard and weight bearable. The cam function is graphically shown in Fig. 4.

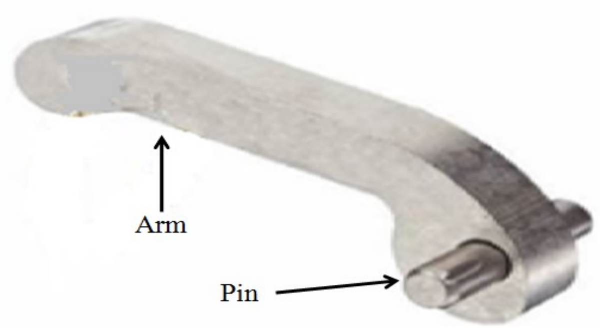

Fig. 3. Basic CAM arm with its pin attachment.

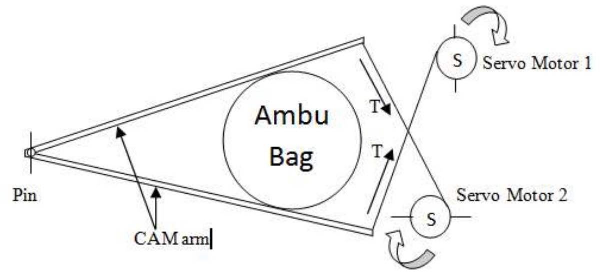

Fig. 4. CAM function with the proposed system (T means tension).

E. Bag-Valve-Mask (BVM) Mechanism

The Bag-valve-mask was also known as manual resuscitator is a mechanical system that intelligently delivers air to a single direction when it is compressed and takes air from the environment when relaxation takes place [1]. In a proper way, BVM ensures air and oxygen from the environment to the patient. There are three inlets in the Ambu bag used in this project. One is for the environmental air inlet. The second one is for the connection pathway of oxygen reservoir and the third one is for the loss minimization. Out of that, there is a single pathway for emergency air circulation. There is a single outlet of the Ambu bag that is used to connect the patient for air inhalation. There is a one-way valve in the outlet of a BVM Ambu bag. Out of that, there is also a single air pathway at the outlet side of it for emergency exhalation. Some emergency patients need a high volume of oxygen approximately tends to hundred percent oxygen otherwise dangerous hypoxia occurs where hypoxia is the oxygen deficiency in the abiotic environment.

F. Mathematical Formulation

Child mode (1-12) month aged child has a tidal volume of (4-6) milliliter per kilogram. Pediatric mode (6-11) years an aged person has a tidal volume of (5-8) milliliter per kilogram. Adult mode (18 or more) years an aged person has a tidal volume of 7 milliliters per kilogram. So, for example generally, the tidal volume of 23 years and 61 kilogram weight adult person is equal to (7 ml/kilogram×61 kilogram) or 427 ml. In this way, we can calculate the general tidal volume of all aged person.

The diameter of the pulley is 4.3 centimeter, so the circumference of the pulley is 27 cm approximately. As we have two servos operating on 180 degrees or two right angles at a time, so the cot wire can oscillates within (27/2)×2 = 13.5×2=27 centimeters. Arm length is 40.50 centimeter. Relax angle or initial angle is 37.94 degrees or 5.1/7.7 radian and compress angle or final angle is 18.2 degrees or 2.45/7.1 radian for an adult. Now we want to find out the angle between two CAM arms because the output volume depends on the angle between two arms.

We know that the arc length of a circle is $S = r\theta$, where the angle θ is in radian and r is the radius. We have three circles, two pulleys which act like a circle and another imaginary large circle is considered where CAM arm is the radius of that large circle. As we have two pulleys, we take $S_p = S_{p1} + S_{p2}$ *where* S_{p1} is the arc from the first servo motor and S_{p2} from the second servo motor. For 180 degree or π radian rotation of pulley the imaginary circle covers a small arc Sa. So it can be said that S_a is equal to S_p, then $r_a\theta_a = r_p\theta_p$. Finally, we get Eq. (1).

$$\theta_a = \frac{r_p\theta_p}{r_a} \tag{1}$$

We know that as large as the radius of the pulley, it covers large arc S_a of the largest circle shown in Fig. 5 (left). Therefore, $r_p \; \alpha \; \theta_a$ and we get Eq. (2).

$$r_p = k_1\theta_a \tag{2}$$

Where k_1 is the proportional constant that depends on r_p and θ_a. Another proportional constant k_2 is found where θ_a is proportional to the output volume (V) of the Ambu bag results for compression on it by the mechanical CAM arm as written in Eq. (3).

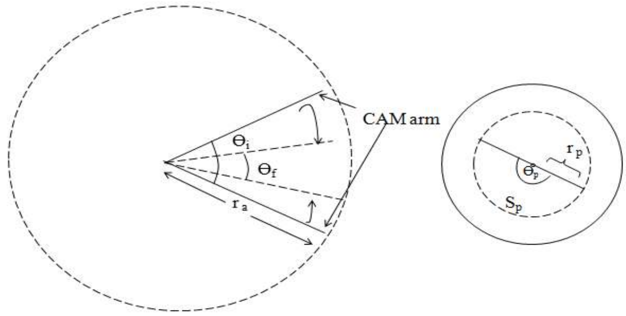

Fig. 5. (Left) Large imaginary circle to measure of $\theta_a = \theta_i - \theta_f$ and (Right) Pulley structure to calculate different angles.

So, we can write $\theta_a \alpha V$ or $\theta_a = k_2 V$ (3)

From Eq. (2) & Eq. (3), the relationship between pulley radius and oxygen output volume is obtained that is shown in Eq. (4).

$$r_p = k_1 k_2 V = kV \tag{4}$$

Since k is constant, therefore, the radius of the pulley is proportional to the volume output of the Ambu bag.

In the above analysis, θ_a is the difference between an initial angle and final angle, θ_i is the initial angle, θ_f is the final angle, V is the volume output that means the tidal volume, r_a is the radius of the large circle shown in Fig. 4(left) that means the length of the CAM arm, r_p is the radius of both pulleys. Here, S_a is the arc covered by the large imaginary circle described before.

G. Proposed Circuit Diagram

The circuit diagram consists of resistors, microcontroller, servo motors, switches, and power supplies. The input and output pins are set to the digital pin of the microcontroller. A 12-volt power supply is added to get high torque from the servo motor. The electronic circuit diagram of the proposed system is shown in Fig. 6.

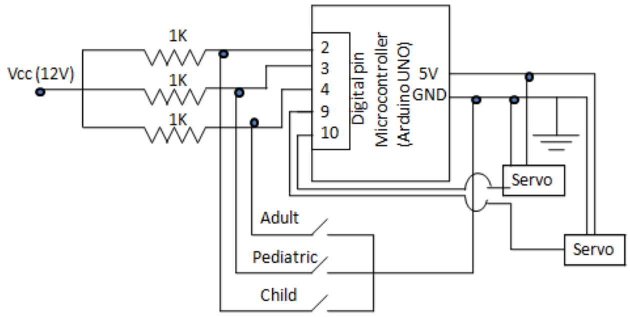

Fig. 6. Electronic circuit diagram of the proposed system

III. System Architecture and Hardware

A. System Architecture

This architecture shows the combination of all hardware part of the system that is stable with a hardware frame. Oxygen cylinder is used with a control opening. An oxygen tube is connected with an oxygen cylinder and Ambu system. Our environment contains about 23 percent oxygen. So we can take it through another inlet to reduce loss. The system architecture is shown in Fig. 7.

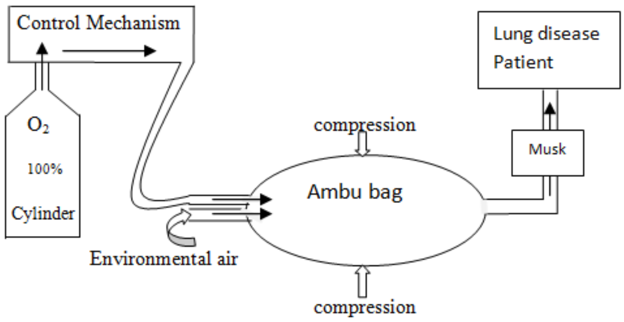

Fig. 7. The architecture of the proposed system making a way of oxygen delivery.

B. Hardware Implementation

The actual hardware implementation of this project is shown in Fig. 8. The hardware implementation is one of the most important as it is a challenge to reduce mechanical error. The hardware design consists of the following: microcontroller, wood frame, CAM arm made by PVC, servo motor, switches, pulleys, DC 12 volt battery, Ambu bag, jumper wires, etc. The top, front and right side view of the hardware implementations are given below in the figures respectively.

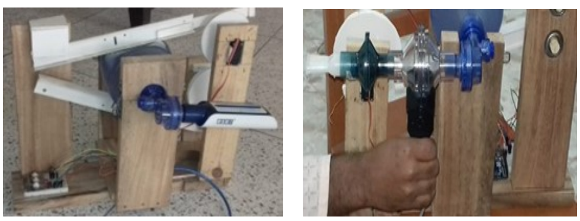

Fig. 8. Experimental setup with BSL SS11LA airflow transducer (right) and with a peak flow meter (left) of the proposed system.

C. Facilities and Advantages

There are some attractive facilities of the Ambu bag with this proposed system. Clinicians offer patients to use age wise different Ambu bag. Such as adult Ambu bag, the silicon Ambu bag is the self-inflating system. Here we need only to compress it. After compression when decompress it inflates itself. This is the most attractive feature of silicon Ambu bag. Ambu bag can be sterilized easily although it is non-autoclave-able. There are two emergency airways at the inlet and outlet side. Another attractive feature of Ambu bag with this proposed system is that instead of using three Ambu bag (such as for Adult, Pediatric and Child Ambu bag) one Ambu bag is used to perform different modes by controlling it with a microcontroller. The adult BVM system is about 1650 ml that is enough to deliver the minimal tidal volume to all aged patient using the control mechanisms. In the future, some more additional advantage can be integrated with this proposed system to improve it.

D. Drawbacks, Hazards, and Solutions

Misassemble of Ambu bag sometimes occurs for the cause of using an Ambu bag for so many days as the manufacturing material have fracture properties. To avoid this problem Ambu bag can be replaced. The second one is the Bacteria and Germ attack from the environment while filtering is not used. The third reason is the ventilation difficulty of the BVM system because of not replacing after long-term use. The fourth one is improper BVM selection. All of this problem can be solved by using proper hardware implementation and technique development. After all the entire germ attack is the main problem of an Ambu bag. Germ attack can be reduced by using a filter at the inlet of the bag and the filter may be changed every day after use per patient. However, in a developing country like Bangladesh has no in-house clinical engineer in any of the ICU which represents the inferior type of clinical engineering interaction with life support ventilator [3, 10].

IV. Results and Discussions

We have measured three of our output data with respect to the input. They are data of angle, data of tidal volume (TV) and data of respiratory rate (RR). The command angle is generally measured from the large circle that is shown in Fig. 4 (left) without any Ambu bag and the output angle is measured with the Ambu bag. This is why the Ambu bag is like a load in the system of the device. So we found the efficiency of the whole system while we got a different angle at with load and without load for the same input. The angle errors are shown in Table I. this angle error results for the insufficient torque of the servo motor.

In Table II, we have discussed the tidal volume output. All the separate command angles that described in Table I, we measured the command volume in the same way. Then after Ambu bag insertion, we found some variation in the output tidal volume. As our servo was DC servo with 180-degree angle highest rotation, this is the highest output for our hardware device, rather than we can get a more accurate result by changing the hardware structure. In Table III respiratory rates are discussed. We chose some respiratory rate according to the age of a patient named command respiratory rate or command RR and beside them, the observed respiratory rate is displayed. The negative percentage refers to the high observation than input command. The tidal volume graph of an adult, pediatric and child mode respectively collected from Biopac Student Lab system as a portion of spirogram is described by Fig. 9, Fig. 10 and Fig. 11 [11]. An adult person has a low frequency of RR than a pediatric boy or a child. On the other hand, adults have a high amplitude of air volume that is clearly notified from the output graph. The average peak to peak value describes the tidal volume that is found 395, 243 and 71 for adult, pediatric and child mode respectively. For some experimental result, we have used some standards displayed in the command. We can alter the command standards and add several modes more to find out more accurate results that would reduce errors. These are our final outputs.

TABLE I. MEASUREMENT OF INITIAL ANGLE AND FINAL ANGLE FOR DIFFERENT MODES

Mode	Command angle (degree)	Initial angle (degree)	Final angle (degree)	Output (difference of angle)	Error
Adult	19	37.9	19.7	18.2	4.71 %
Pediatric	16	37.9	23.1	14.8	6.91 %
Child	10.5	37.9	27.8	10.1	5.66 %

TABLE II. MEASUREMENT OF OUTPUT VOLUME AND ERORR CALCULATION FOR DIFFERENT MODES

Mode	Command volume (ml)	Output volume (ml)	Volume error
Adult	430	395	8.13 %
Pediatric	260	243	6.53 %
Child	65	71	-8.85 %

TABLE III. MEASUREMENT OF RESPIRATORY RATE CALCULATION FOR DIFFERENT MODES

Mode	Command RR (breath/minute)	Output RR (breath/ minute)	RR error
Adult	20	21	- 5 %
Pediatric	30	34	- 13.33 %
Child	60	67	- 11.67 %

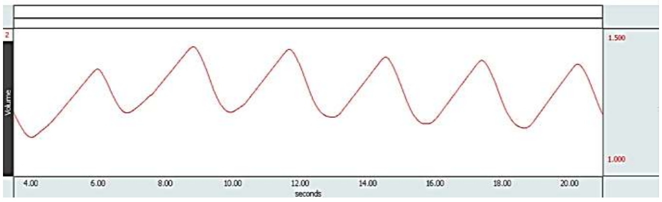

Fig. 9. Spirogram of tidal volume for an Adult male collected from BSL integration with our device. (Tidal volume is 395 ml approximately found)

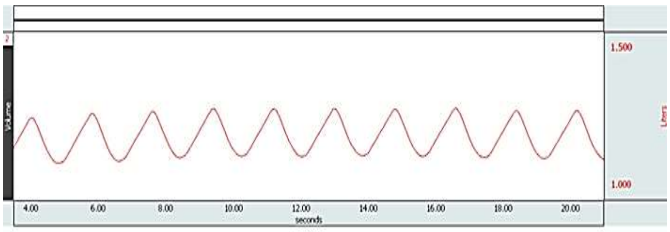

Fig. 10. Spirogram of tidal volume for a pediatric boy collected from BSL integration with our device. (Tidal volume is 243 ml approximately found)

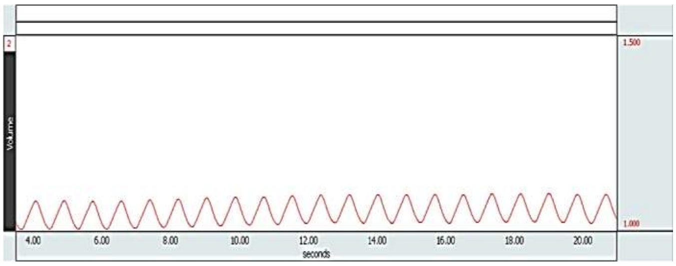

Fig. 11. Spirogram of tidal volume for a child collected from BSL integration with our device. (Tidal volume is 71 ml approximately found)

The command values of angles in Table I are found by the calculation in the programming section of the microcontroller and the output value of angles are the measured value. Based on these angles and structure of Ambu bag, the command volume and respiratory rate are identified and output of them are the measured parameters that are collected from Biopac BSL software [11]. Between the calculated and measured value, the efficiency or error is found out easily while the measured values are the outputs.

V. CONCLUSIONS

Our goal is to implement such a ventilator system that is stable, portable, high efficient, low powered or battery operated, easy to use, riskless, repairable and reusable. Although we could not fulfill all facilities we want, we efficiently show the output at so near to the exact output values. In the future, we can develop another technology to find out the tidal volume and respiratory rate automatically using sensors that will be implemented with the ventilator system and according to the physiological parameters, the control signal that means the tidal volume can be generated. After all mechanical ventilator is a growing technology in this world now for the automation basics like telemedicine applications. Smart ventilators may be a large field for both in clinical cure or research field in the near future.

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