Design and Control of a Portable Mechanical Ventilator*

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***Abstract*–The aim of this work is to design and control of a mechanical ventilator with the simplest strategy that satisfies the need for low-cost mechanical ventilation. This design should be rapidly manufactured in large quantities to make it possible to safely ventilate a COVID-19 patient. The process in approaching that, is to first identify the minimum requirements for a low-cost ventilator, based on the information of many clinicians with respect to the design against these requirements, conducting immediate testing, reporting the results. Two different ventilator concepts are proposed, such that the ventilator can be operated in case of a pressurized air-oxygen mixture is available or not. The proposed design is inspired by medical professionals and adult patients battling COVID-19. It allows gentle air delivery to the patient with capability for both volume control and pressure support modes. The mechanism design is user-friendly and easy to manufacture, the sophisticated control system ensures flexible inputs, patient data monitoring, and various levels of alarms. Simulation results and experimental work are presented and have shown to be applicable compared to previous works.**

Keywords—Mechanical ventilation, mechatronics, control engineering, biomechatronics, biomedical engineering.

I. Introduction

Mechanical ventilation is essential in the intensive care unit (ICU) for the life support of patients who have lung dysfunction due to illnesses like pneumonia, COVID-19, and others. The mechanical ventilation process provides and regulates air and gas flow, pressure, and volume to a patient's lungs. Mechanical ventilation aims to achieve the best possible positive end expiration pressure (PEEP). Mechanical ventilation is essential in the intensive care unit (ICU) for the life support of patients who have lung dysfunction due to illnesses like pneumonia, COVID-19, and others as given in [1],[2]. The mechanical ventilation process provides and regulates air and gas flow, pressure, and volume to a patient's lungs. Mechanical ventilation aims to achieve the best possible positive end expiration pressure (PEEP). Both types distribute and control air and medicinal gases to the patient's lungs in terms of flow, pressure, and volume. VCV is a treatment for disordered lungs that delivers a consistent volume to the patient's lungs. Mathematical models can help solve difficult engineering issues in a realistic way. The lung mechanics of a patient can be described using a mathematical model as shown in [3],[4],[5].

The pneumatic system leverages the compressed air and oxygen already within a hospital room to minimize mechanical complexity and material fatigue. The flow from each line (air, O_2) is controlled via solenoid valves into a 700cc, custom made, gas blending chamber O_2 and pressure sensors. The combined flow is then regulated (to enable gentle delivery) via an equipped with proportional solenoid valve through a pressure sensor, a flow sensor, a pressure relief valve, and a hygroscopic condenser humidifier and filter (HCHF) to the patient. The flow on the expiratory side, which is controlled by another solenoid valve, passes through a pressure sensor, flow sensor, and PEEP valve before being discharged as given in [6],[7].

The aim of this work is to derive and evaluate concepts for a mechanical ventilation Device supported with 2 modes (pressure control and volume control) with the simplest strategy that satisfies the need for low-cost mechanical ventilation. In Section II the system description regarding the clinical perspective and key ventilation specifications is shown. In Section III, the system design approach with respect to power calculations, motor selection, and plumping is presented. In Section IV the system modelling with respect to the dynamics is presented. Control Design is shown in Section V. Simulation results are shown in Section VI. The experimental work is illustrated in Section VII. Conclusion and future work are shown in Section VIII.

II. System Description

A. Clinical Perspective

Ventilator is planned for emergency use only when all accessible conventional invasive respiratory support has been worn out. It should only be applied in a clinical environment

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under careful observation by trained medical professionals. There were two critical assignments which we started with: Pick out potential use scenarios and define the minimum safe clinical functional specifications as shown in [8],[9],[10].

- *Anticipated Clinical Scenarios*
  - Patient, who is choking, out of breath and hypoxic; hypoxemic respiratory insufficiency means they are not breathing well enough to sufficiently oxygenate their blood.
  - Declining clinical status recognized when a patient develops (ARDS) acute respiratory distress syndrome is a type of respiratory failure shown by rapid onset of widespread inflammation in the lungs. Symptoms contain shortness of breath (dyspnea), rapid breathing (tachypnea), and bluish skin coloration (cyanosis)
  - The patient will be intubated or have a tracheostomy (limited / no applicability to mask)
- *Minimum Safe Clinical Functional Specifications*
  The minimum safe clinical functional specification can be shown in Table I.

TABLE I
MINIMUM SAFE CLINICAL FUNCTIONAL SPECIFICATIONS

Parameter	Value or range	Notes
Modes	Volume Control Assist Control Fail-safe	Recognize if patient. Stops breathing then switch. To default
Tidal volume	200-800 ml 6ml or less/kg As start point	Must be adjustable.
Rate	8-40 / 10-40 per minute	Must be adjustable.
PEEP	5-20 cm H_20	Must be adjustable.
Plateau pressure	Threshold:40-60 cm H_20 Achieve with valve	Usually fixed depending on Ambu bag type
I/E(inspiratory/ expiratory ratio)	1:2; range of 1:1 – 1:4 COVID-19 patients are frequently requiring 1:3 and higher	Adjustable
Expired filtration	HEPA available as a component	-
Inspired filtration	HEPA available as a component	-
Inspired humidification	Combine with outgoing (self-humidification)	-
Assist Control (breath detection or trigger sensitivity)	Sense pressure of -1 to -5 cm H_20	Recommended – requires pressure transducer in design
FiO_2	30%-100%	-
Peak inspiratory pressure (PIP)	Will be set by pop off valve threshold in initial product. If pressure transducer is used to continuously measure airway pressure, can program to limit PIP	Fixed or Adjustable – requires pressure transducer in design

B. Key Ventilation Specifications

- Respiratory rate (RR) (breaths per minute): Between 6 to 40 that only for Assist Control are the low RRs of 6-9 applicable.
- Tidal volume (TV) (air volume forced into the lung): as a starting point of 200-800 mL dependent on patient weight of 6 mL or less / kg (ideal patient weight).
- I/E ratio (inspiratory/expiration time ratio): advised to start about 1:2; better if flexible from 1:1 to 1:4. COVID-19 patients also require 1:3 and higher.
- A Trigger Sensitivity is dependent on Assist Control (breath detection): When a patient attempts to inspire, they will induce a dip in the order of 2 to 7 cm H_2O with respect to PEEP pressure (not necessarily equal to atmospheric pressure). COVID-19 patients who develop ARDS have an underlying, restricting condition that needs extra baseline pressure to help sustain gas exchange by "prop" open alveoli. Done by Positive end-expiratory pressure (PEEP).
- Airway pressure must continually be monitored. At any time, maximum pressure should be limited to 40 cm H_2O.
- The plateau pressure should be restricted to a maximum of 30 cm H_2O.
- It is extremely important to use a passive mechanical blow-off valve fixed at 40 cm H_2O. This is built into most resuscitators that are manual.
- Note Clinician require plateau pressure and PEEP reading.
- A 5-15 cm H_2O PEEP is required; 10-15 cm H_2O is required for many patients.
- Failure conditions must result in an alarm to enable conversion to manual override by the clinician, i.e., if automatic ventilation fails, the conversion to immediate ventilation must be immediate.

III. SYSTEM DESIGN

A. Mechanical Ventilator

The essential principle is that the bag is compressed by two arms closing softly in rhythm as shown in Fig. 1. This should be used in conjunction with a closed-loop control system. The following are some of the most important mechanical design requirements:

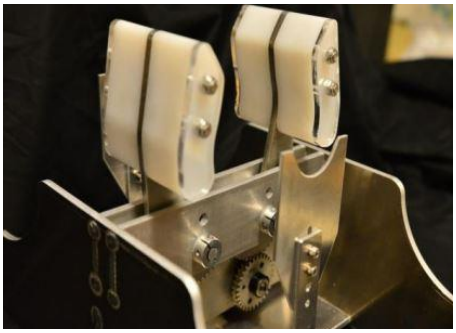


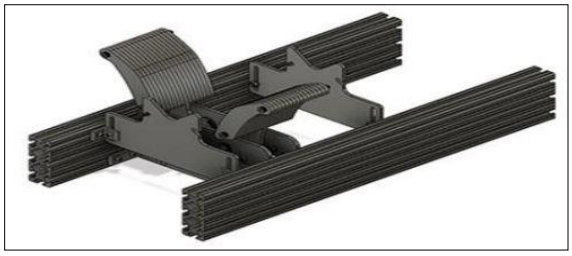
Fig. 1 The two arms pressing mechanism

Up to 7 days × 24 hour × 60 minute × 30 bpm × 2 stroke = 604,800 cycles are required for 7-day usage. To decrease the risk of material fatigue, every configuration must safeguard the bag by gently gripping and pinching it on all sides. To maximize the expelled air without disrupting the container, the grippers must be smooth and contoured. To allow for movement during service, the bag has to be versatile as given in [11],[12].

Fail-Safe-If the system fails, the clinician must be able to shut down automatically, manually open the unit, remove the bag and turn it to manual bagging. This radial load is applied roughly 2 cm from the face of the gearbox to the pinion, resulting in a twisting stress on the shaft of the gearbox that the gearbox bearings have to endure.

Material selection is extremely important, based on the readily available materials, we prototyped. As a function of your material selection and component width, arm gear and driving pinion life must be tested for wear and fatigue as given in [13],[14],[15].

Aluminium is not recommended. Steel gears are recommended, but not stainless because it will gall/spall. Life will be increased by hardening the steel gears and adding lubrication. The main frame used for assembly is shown in Fig. 2.



Fig, 2 The main frame used for assembly

Power Calculations

Independent of the gripper design, the required output power can be calculated from the worst-case values of the next variables:

Independent of the gripper design, the required output power can be calculated from **the worst-case values** of the showing variables:

- The maximum pressure at airway: $P_{airway,max} = 40\ cm\ H_2O$ (pop off cracking pressure)
- The maximum respiration rate: $RR_{max} = 40\ bpm$
- The minimum inhale/exhale ratio of 1:4: $IE_{ratio,min} = ¼.$
- The maximum volume output: $V_{max} = 800\ cm^3$

That is, in the worst case the device needs to squeeze of air at a pressure of 40 cm H_2O, in 0.3s

$$t_{inhale} = \frac{60\ sec\ /RR_{max}}{(1 + IE_{ratio,min})}. \quad (1)$$

The volumetric flow rate needed in the worst-case (peak) scenario is, then:

$$Q_{airway} = V_{max}./\ t_{inhale} = 0.0027\ m^3/s \quad (2)$$

The power output (in the form of pressurized volume flow in the airway) is:

$$Power_{airway} = P_{airway,max.}.\ Q_{airway} = 10.460\ W. \quad (3)$$

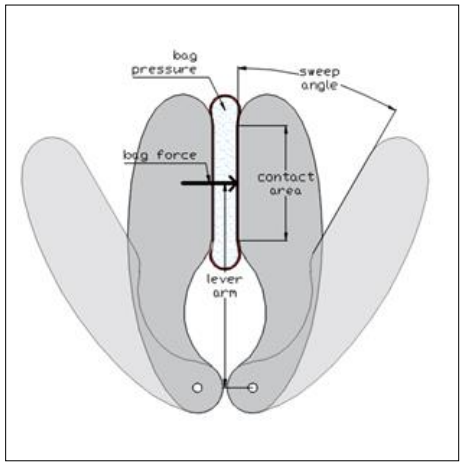
However, some of the power used for squeezing the bag is lost (bag deformation, friction, etc.) and let us estimate that 50% is converted to pressurized volume flow. Taking this efficiency into account, the power required at the gripper is:

$$Power_{gripper} = 2\ Power_{airway} = 20.920\ W \quad (4)$$

The actual power needed from the motor will be higher, how much higher depends on the electrical and mechanical designs. Assuming the half of the power output of the motor is lost to mechanical and electrical inefficiencies (gears, thermal dissipation, etc.), the power output required from the motor is:

$$Power_{motor} = 2\ Power_{gripper} = 41.840\ W \quad (5)$$

This is an alternative approach for calculating the power in case of 2-finger design asshown in Fig. 3. The following is an illustration of a 2-finger gripper design as given in [16],[17],[18]:



Fig, 3 The finger gripper design

A more direct approach can be used for this design provided the following quantities can be measured:

- Finger-bag contact area.
- Finger lever arm length
- Sweep angle

For one particular prototype, we have:

Finger-bag max contact area: $A_{bag} = 90\ mm \times 115\ mm$

Finger lever arm length: $l_{finger} = 12\ cm$

Sweep angle: $\alpha_{sweep} = 30°$

The maximum force of the bag on one finger (when fully squeezed) is, using the same 50% pressure transmission efficiency as before:

$$F_{finger} = 2\ A_{bag.} P_{airway,max.} = 81.199\ N \quad (6)$$

The maximum torque needed on each finger is then:

$$T_{finger} = F_{finger}.l_{finger} = 9.74\ N.m \quad (7)$$

Now we can compute the power required for the two-finger gripper using the sweep angular rate (in 0.3 second):

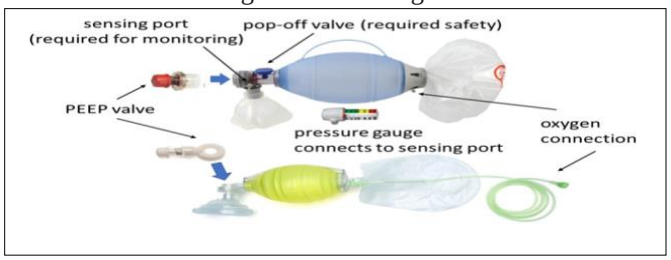
$$P_{gripper} = 2 \times T_{finger}.w_{finger} = 34.01\ W \quad (8)$$

The total power for the motor (assuming a single motor) when additionally applying the same 50% motor and gearbox efficiency, we get:

$$P_{motor} = 2 \times P_{gripper} = 68.03\ W \simeq 70\ W. \quad (9)$$

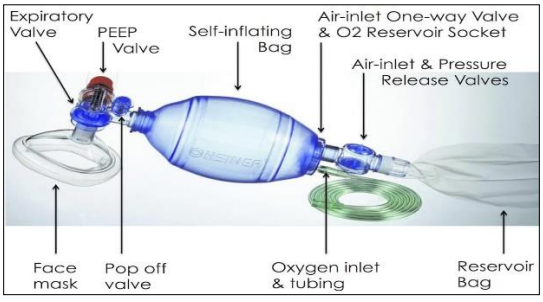
The minimum motor power is approximately 70 W. Therefore, a power supply at 12 V should be specified with a minimum of a 5.8 (~6 A) supply.

Normally, the patient's endotracheal tube adapter is connected to self-inflating manual resuscitators. Manual resuscitators have a "patient valve" the patient valves hunt the exhaled gas or air to the environment, and it directs air/oxygen gas mixture to the patient. There are some features integrated into the end of the bag valve mask (BVM): Oxygen connection and reservoir as given in [19],[20],[21]. The components of a manual resuscitator bag is shown in Fig. 4.



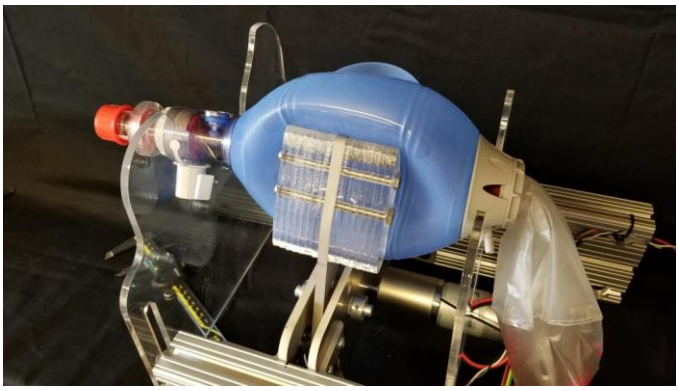
Fig, 4 The components of a manual resuscitator bag

The bag valve mask (BVM) is shown in Fig. 5. When a manual resuscitator is placed into an Emergency Ventilator, or similar design, the system cannot be placed right up against the patient's head. In addition, patients need to be turned intermittently for routine care and patients can thrash and move in their beds. Even when patients are paralyzed, the paralytic may wear off at times and we must consider how to keep the patient safe from inadvertent breathing circuit disconnection or extubating. Therefore, a safe method to extend the "reach" and flexibility of the manual resuscitator to a patient lying on a hospital bed is needed. If a simple tube is used to do so, it creates a critical safety concern of "dead space."



Fig, 5 Bag Valve Mask (BVM) ventilation

Between the grippers, the bag should be balanced laterally and vertically as shown in Fig. 6. At the touch points and the middle of the bag. Table II below provides the dimensions as given in [1],[22].



Fig, 6 The Ambu bag mechanism

TABLE II
Ambu Bag Parameters

Bag	distance	bottom ø	top ø	center ø
Ambu Spur II & Adult Silicon	21	61	29	129
Care Fusion	21	54.5	50	134
Portex	20.5	61.5	37	131

In Table III, the clinical parameters for the bag valve mask with respect to volumes and ages for adult, child, and infants are specified.

TABLE III
Volume and Ages

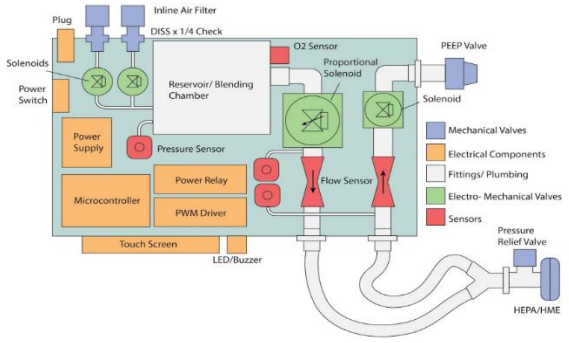
BVM	Adult		Child		Infant	
	Absolute volume (ml)	Tidal volume (ml)	Absolute volume (ml)	Tidal volume (ml)	Absolute volume (ml)	Tidal volume (ml)
Ambu Spur II[2]	1475	600	635	450	220	150
Laerdal The Bag II[2]	1650	830	500	330	230	180
Merlin[3]	1794	830	665	330	350	180

B. Pneumatic Ventilator

To minimize mechanical complexity and material fatigue we decided to make a pneumatic ventilator. The system depends mainly on controlling the air and oxygen flow from reservoirs using valves and sensors. The system includes both volume control and pressure support modes so that the patient can be supported throughout the treatment process from intubation to liberation from mechanical ventilation. The pneumatic system diagram for the ventilator is shown in Figure 7.

The pneumatic system leverages the compressed air and oxygen already within a hospital room to minimize mechanical complexity and material fatigue. The flow from each line (air, O_2) is controlled via solenoid valves into a 700cc, custom made, gas blending chamber equipped with O_2 and pressure sensors. The combined flow is then regulated (to enable gentle delivery) via a proportional solenoid valve through a pressure sensor, a flow sensor, a pressure relief valve, and a hygroscopic condenser humidifier and filter (HCHF) to the patient. The flow

on the expiratory side, which is controlled by another solenoid valve, passes through a pressure sensor, flow sensor, and PEEP valve before being discharged.

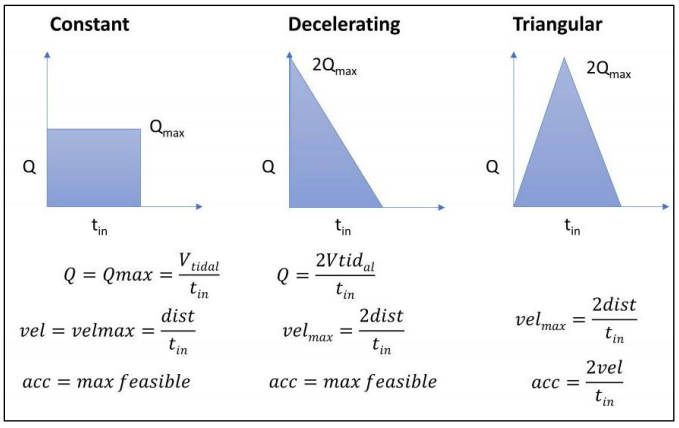


Fig, 7 Pneumatic ventilator system design

IV. System Modeling

This section represent waveforms for a set of test settings are obtained via both a model-based approach where the breathing circuit, the lung and the flow profiles are modeled; and via a data-driven approach where response data is collected using an ASL 5000 breathing simulator connected to the ventilator. In volume control ventilation, a common approach is to supply volume at a constant flow during the inspiratory time. This requires a short rise time and short fall time to approximate a square wave, shown at left in Figure 2, as closely as possible. The peak inspiratory pressure (PIP) for a constant flow profile is expected at the end of the inhale duration when maximum pressure due to compliance is added to the constant pressure due to the constant flow flowing through the airway resistance. Ideally, a perfect constant flow achieves a minimum peak flow needed to deliver a specified tidal volume.

For the Emergency Ventilator this requires a very high acceleration of the arms at the beginning of a breath. This leads to a consistent resistance pressure and growing compliance pressure. As an alternative, physicians recommend a decelerating flow profile, whereby the flow starts high and decreases to zero as the desired Tidal Volume is reached, shown at middle in Fig. 8. A triangular flow covering the same area (delivered tidal volume) as a constant flow would require a peak flow that is twice that from a constant flow profile.



Fig, 8 Respiratory flow profiles and commanded motor velocities and torques

The triangular flow profile was developed in response to testing, which indicated that the Emergency Ventilator motor and controller were struggling to achieve the "infinite" acceleration necessary to ramp up to a constant flow profile. This is a compromise flow / motion profile, shown at right ion Figure 2, whereby the motor speed ramps up and then down. If the max velocity exceeds the motor capabilities, it can be capped for a trapezoidal flow.

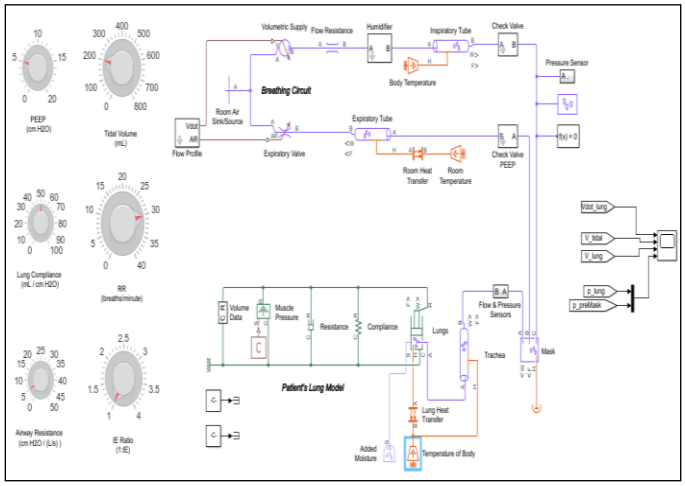
Calibration: Prior to testing, the Emergency Ventilator was calibrated for an Ambu Oval Silicone Resuscitator. The resulting slightly quadratic curve is shown in Figure 3. This curve starts at 300 ticks, the rest position measured from zero, just touching the bag. The curve is given by:

$$ticks = \frac{-b+\sqrt{(b^2-4\times a\times(c-vol_{ml}))}}{2\times a}. \quad (10)$$

$$a = 1.29\times10^{-3}\ ;\quad b = 4.73\times10^{-3}\ ;\quad c = -7.35\times10^{1}$$

This calibration is specific to each bag and system and by inspection is approximately linear. This curve was used to set the mechanical endpoints as a function of desired Tidal Volume, but not to adjust the motion profile.

The pneumatic circuit including all the system components is represented in Simulink as shown in Fig. 9.



Fig, 9 The Simulink model

This model represents a positive-pressure medical ventilator system. A preset flow rate is supplied to the patient. The lungs are modelled with the Translational Mechanical Converter (MA), which converts moist air pressure into translational motion. By setting the Interface cross-sectional area to unity, displacement in the mechanical translational network becomes a proxy for volume, force becomes a proxy for pressure, spring constant becomes a proxy for respiratory elastance, and damping coefficient becomes a proxy for respiratory resistance.

V. Control Design

A. The Mechanical Ventilator

The high-level controller goal is providing a controlled air volume to the patient in a specific time. There are two phases

of control, that are the inspiratory phase and the expiratory phase.

Few input parameters are needed:

-Tidal Volume (V_T): The total volume of air delivered to the patient.
-Breaths Per Minute (BPM): Typically varies between 8-30 BPM, also called respiratory rate (RR).
-I/E Ratio (1: IE): The ratio of the duration of the inhale to the duration of the exhale.
-Trigger Sensitivity: This parameter is basically relevant to the (assist control) mode and sets the pressure threshold below PEEP for triggering a patient-triggered inhale cycle.
The volume control state machine is shown in Fig. 10.

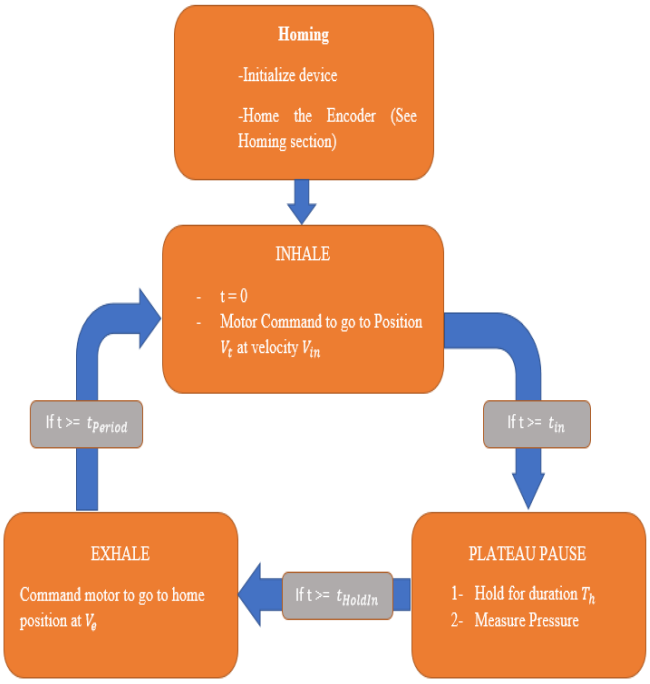


Fig. 10 Volume control state machine

The system needs two more inputs such like the position of the motor encoder beside the system pressure. Its purpose is translating all the inputs into desired speed and position of the motor.

Assist Control differs from regular volume control in that the Exhale state is split into 3 states. In the first Exhale state, the fingers move to their home position at the edge of the bag. In the second state, Exhale Pause, the fingers pause for a short time and measure the PEEP. In the third state, Listen, we wait either for the patient's own inhalation to trigger the Inhale state, or we wait for a set amount of time (like in normal Volume Control) and then trigger the Inhale state automatically. In the Assist Control mode, a notification (not necessarily a full alarm) should also sound whenever a breath is NOT activated by the patient and the system's timer kicks in to command a breath. Other faults must be detected, such as mechanical failures to reach desired positions, etc. as shown in Fig. 12.

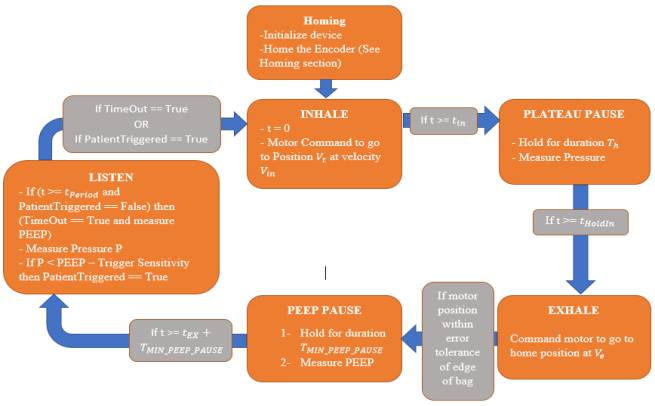


Fig. 12 Assist control

B- Pneumatic Ventilator

When designing a PID controller, one must go through a tuning process where different gains are tried until the controller is correctly tuned for a specific application. In VC mode our PID controller receives the readings from the inspiratory flow sensor as input and compares it to a desired flow rate calculated using the user-set tidal volume, I:E ratio and BPM, as shown in (11).

$$Desired\ Flow = \frac{TV \times BPM \times (1+IE)}{IE \times 1000}. \quad (11)$$

Where, TV is set tidal volume in L/min, BPM is set breaths per minute, IE is the set IE ratio. The factor of 1000 converts the flow units to cc/min, as measured by the sensor. To minimize oscillation of our system, the sensor reading input to the controller is actually an average of the last 4 recorded flow values rather than the most recent reading. The controller outputs a pulse-width modulation (PWM) value that corresponds to a specific opening position for the proportional valve on the inspiratory line. A diagram of the VC mode PID controller can be found in Fig. 13. Following the Ziegler-Nichols tuning method, we arrived at the following constants for the VC PID controller: K_p = 0.225, ki = 1.08, and K_d = 0. The zero value for K_d worked fine during initial tests but during subsequent operation we observed some minor oscillations. Most likely, a small (<0.01) derivative constant would be better, so we recommend additional tuning as part of future work for both VC and PS modes.

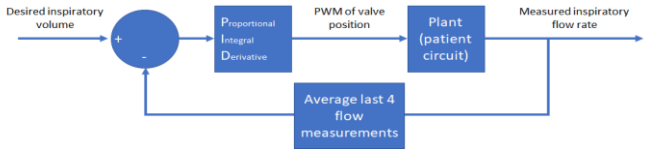


Fig. 13 Volume control mode PID controller

VI. Simulation Results

Using the Simulink model given in Section IV, two test profiles are applied. The first test is based on a constant flow profile using the parameters shown in Table IV. The other system variables as the tidal volume, lung volume, and lung pressure can be seen in Fig. 14.

A. Constant flow profile

TABLE IV
Test parameters for constant flow profile

Test No.	1
Compliance (ml/cm H2O)	50
Compliance (ml/cm H2O)	5
Volume (ml)	500
Ventilator Frequency1 (breaths/min)	20
Inspiratory: Expiratory ratio	I/E=1:2
PEEP (cm H_2O)	5

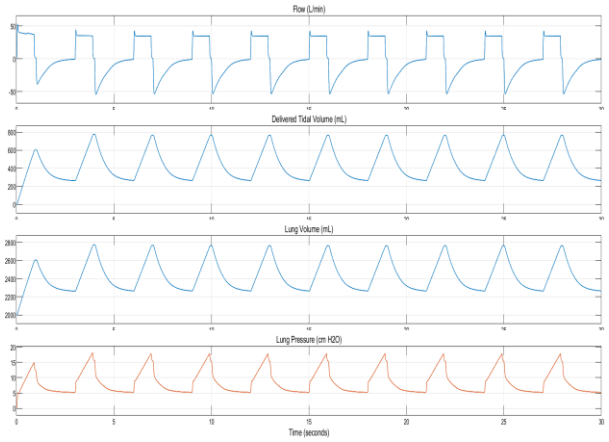


Fig. 14 Test model results with constant flow profile

B. Triangular flow profile

TABLE V
Test parameters for triangular flow profile

Test No.	2
Compliance (ml/cm H2O)	50
Compliance (ml/cm H2O)	20
Volume (ml)	500
Ventilator Frequency1 (breaths/min)	12
Inspiratory: Expiratory ratio	I/E=1:4
PEEP (cm H_2O)	10

The second test is based on a triangle flow profile using the parameters shown in Table V. The other system variables as the tidal volume, lung volume, and lung pressure can be seen in Fig. 15.

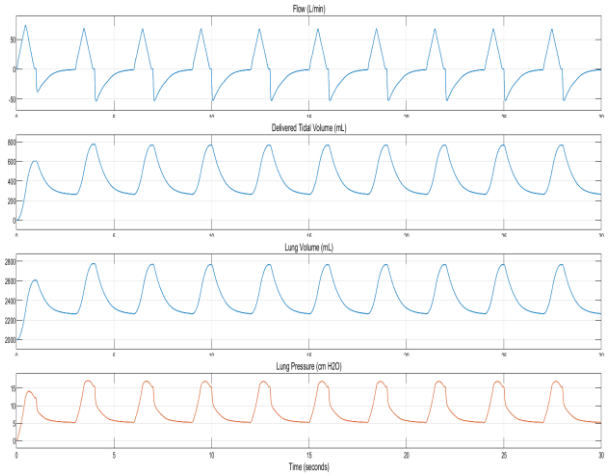


Fig. 15 Test model results with triangle flow profile

VII. Experimental Work

A. Mechanical Ventilator

The data have been collected, by the team, about every single component. All components in mechanical ventilator from Egypt except the RoboClaw shipped & the pressure sensor (Honeywell) from USA. The main components are:

1. Microcontroller it is recommended Arduino Mega in our project as more powerful microcontroller with enough I/O pins (has additional digital, analog, and communication channels)
2. Power supply: It delivers 12V / 5A.
3. Backup Power: It is recommended a backup power source in case of loss power supply source. This backup with a runtime up to 30 minutes.
4. Motor Driver: The RoboClaw is a motor controller, that designed to control DC motor (brushed DC motor) at 60 A and up to 100 A peak.
5. Inputs & Outputs (control interface)
   - Potentiometers:
   TV: Tidal Volume
   RR: Respiratory Rate
   I/E: inspiratory/expiration time ratio
   TRIG: Sets the pressure threshold for detecting assist control. This varies as described in the clinical document.
   - Buttons:
   Stop: A single push must fully depower the whole system. This will allow the bag to be removed and immediate conversion to manual bagging in the case of any major failure.
   Mute: mute the alarm snooze
   Confirm: A set button the start or set the state of each potentiometer
   - LCD:
   Screen displays airway pressure in cm H2O. Other functions can be incorporated later. We are using a 20×4-character LCD display as this will display the minimum information, described in under interface.

6- SD card: The SD card is used to save the patient information. Enter the patient's first and last name, patient ID, contact information, and comments.

7- Limit Switch: It used to control the positions of the arms (mechanism of the ambu bag).

The implemented mechanical ventilator is shown in Fig. 16.

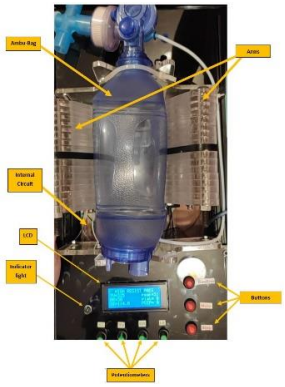


Fig. 16 The implemented mechanical ventilator

The operation step of the mechanical ventilator are as follows:

1. Gently open the fingers by hand if not already open. This takes some force, but it is safe.
2. Position the Ambu Bag in the cradle between the fingers.
3. Ensure that all dials are turned counter clockwise to the lowest position.
4. Check that nothing is in the way of the fingers.
5. Power up the system. The system will start moving immediately and home to the fully open position. Then it will slowly move to the edge of the bag. (This position is hard coded; it could be settable in a more sophisticated version.)
6. Set the desired *Respiratory Rate*, *Tidal Volume*, and *I:E* knobs, and confirm the values on the display. Press the *Set* button to apply.
7. Increase the *Tidal Volume* to a low setting (as determined by clinician) and press the *Set* button to apply. The system will start pumping. Confirm correct operation.
8. Once the machine is confirmed pumping, connect to patient and increase the *Tidal Volume* to the desired larger value and press the *Set* button.
9. Monitor the peak and plateau pressures and adjust parameters as per clinical guidance. PEEP pressure should be observed to match the setting on the PEEP valve.
10. Do not leave the patient unattended.
11. Monitor vital signs, listen for alarms, and respond.
12. If Assist Control mode is desired, increase the *Threshold* knob and press the *Set* button to apply. This will increase the set point with respect to the PEEP.
13. *Respiratory Rate* should beset to less than the expected patient respiratory rate, i.e., the machine waits longer than the patient would.

B. Pneumatic Ventilator

In this project we tried to dispense the complex mechanical design. All component of this design is from abroad so, it tacks time for shipping. In this time, we work on mechanical design as its need to be implemented with 3D printing and laser cutting .When component came to Egypt, we started to collect them together according to previous data to get the final shape. The implemented pneumatic ventilator is shown in Fig. 17.

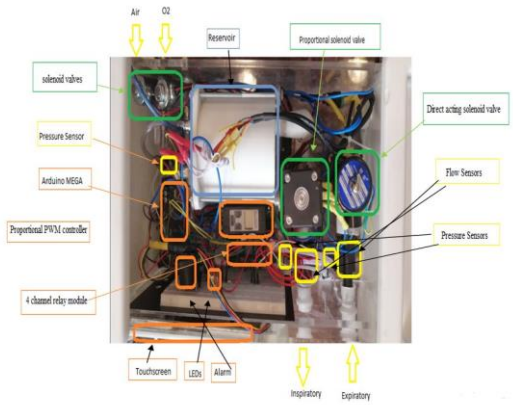


Fig. 17 The implemented pneumatic ventilator

The main components used are as follows:
1- Microcontroller: Arduino MEGA (previously explained).
2- Control Valves:
3- 4 channel relay module:
4- Proportional PWM controller with motor driver board:
5- Sensors
6-Touchscreen:
Both the mechanical and pneumatic ventilators can be seen in Fig. 18.

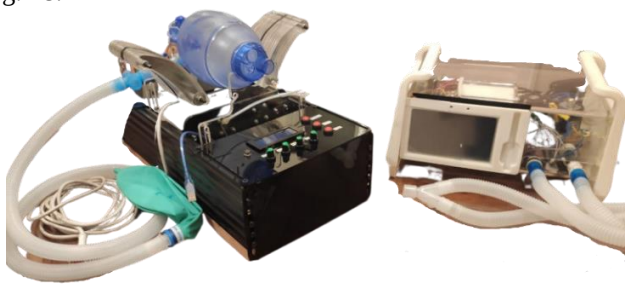


Fig. 18 Both the mechanical and pneumatic ventilators

VIII. Conclusion and Future Work

This project is aimed towards increasing productivity of firms in all countries, especially Egypt by proposing an easy-to-use, easy-to-build and small size mechanical ventilator with a unique design, aiming to prevent massive loss of life in resource-poor environments.

It proposes the Simulation of the Ventilation process with the help of MATLAB (Simulink) environment to observe results and prevent risks, the results show the different responses for different support modes proposed and the Alarm System is to declare any issues. Also, it contains the Mechanical Design, Circuit Schematic and Control Strategy needed to implement the simulation in reality.

With the help of Embedded Systems, Mechanical Design and High-Level Control Strategies, we aim to provide the best-quality, best-price, and safe local Ventilator in Egypt and hopefully propagates towards different markets, learn more, and keep improving. The project was inspired by medical professionals battling COVID-19 in emergencies. It is focusing on a simplified, cost-effective ventilator tailored to COVID-19 patient needs.

As a future work, the following points should be taken into consideration:

- Adaptive control algorithm to cope with parameter variation and non-linearity.
- Automatic system identification for faults detection and maintenance.
- Change the screen to have a compatible screen with the mechanism and to get a graphical response for the output.

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