A Low-cost Ambu-bag Based Ventilator for Covid-19 Pandemic

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Abstract— **The whole world is under the influence of the novel Coronavirus disease-2019 (COVID-19), which hit hard most of the developed and developing countries, leading to the death of millions of people around the world. This disease majorly affects the respiratory tract, which can progress to more severe or potentially deadly conditions such as acute respiratory distress syndrome (ARDS) or hypoxemia, owing to widespread inflammation of the lungs. Conventionally used ventilator devices are quite expensive and require trained staff for its smooth operation. Generally, in developing countries these types of ventilators are limited in numbers and available only at multispecialty hospitals. So as to tackle and fulfill the urgent need of ventilators, we come up with a device which is a low-cost, easy to assemble, portable automated AMBU resuscitator system, that can be easily scaled, to fight the ongoing pandemic. The device provides precise control over various ventilation parameters, such as PEEP, peak pressure, tidal volume, I/E, BPM, while operating in pressure mode.**

Keywords—Covid-19, AMBU bag, Pressure mode, Breaths per minute (BPM), I:E ratio, AARMED.

I. INTRODUCTION

Coronavirus disease-2019 (COVID-19) is a highly infectious disease caused by a novel coronavirus, causing severe respiratory illness which has infected over 171.47 million as per 01 June, 2021 million people all over the world [1]. This disease majorly affects the respiratory tract, which can progress to more severe or potentially deadly conditions such as acute respiratory distress syndrome (ARDS) or hypoxemia, owing to widespread inflammation of the lungs [2-4]. Mechanical ventilators play a crucial role in fighting not only COVID-19, as it assists patients breathing while the underlying disease runs its course. This has led to an increased surge in the demand for mechanical ventilators, with 3-26% of patients infected with COVID-19 (percentage varies across age groups and severity of symptoms) requiring mechanical invasive and prolonged ventilation [5]. But the disruption in supply chains, transport restrictions and various other factors collectively in the ongoing pandemic has put pressure on the supply of ventilators, aimed to reduce the mortality rates [6]. Cheaper alternatives for mechanical ventilation, especially automated artificial manual-breathing units (AMBU) bags, have received wide attention from clinicians, researchers and policymakers, owing to fast production, economical deployment and easy accessibility to a larger portion of the population all across the world. Automated AMBU bags or resuscitator devices aim to assist patient breathing via compressing and releasing the AMBU bags at a specific frequency while delivering oxygen to meet the breathing rate, pressure, tidal volume and other needs of individual patients. Apart from this, these systems provide an edge over their manual counterparts, allowing staff to perform other critical tasks relevant to patient healthcare, rather than manually bagging patients. Additionally, owing to the simple design, low-cost, portability, battery or mains-in powered, simple control systems with few knobs to control variables, these kinds of systems can be easily used during transportation of patients without even requiring specialized training to operate these devices.

Taking advantage of above-mentioned device, various low-cost mechanical ventilator designs have been proposed [7-15]. All these designs have their own merits and demerits, when compared on the basis of their operation efficacy, robust operation, cost, actuation mechanism etc. The common problem with all these designs remains with the air exhaust assembly, which is situated away from patient mouth, can lead to intermixing of CO_2 with incoming oxygen flow. Also, these system designs are made from specialized parts, making them inaccessible in remote areas of the world.

Here in, we have designed a low-cost, easy to assemble, portable automated AMBU resuscitator system with proper air exhaust assembly that can be easily scaled, to fight the ongoing pandemic. The device provides precise control over various ventilation parameters, such as PEEP, peak pressure, tidal volume, I/E, while operating in pressure mode. The system uses an AMBU resuscitator, which is pushed using 3D printed arms, that is driven using a belt-pulley system, powered by 4 stepper motors. The whole device is assembled in a wooden box (cheaply available) or easy to manufacture by minimal skills required, which can be easily lifted and transported. Additionally, it uses easily available electronic components which are assembled using simple

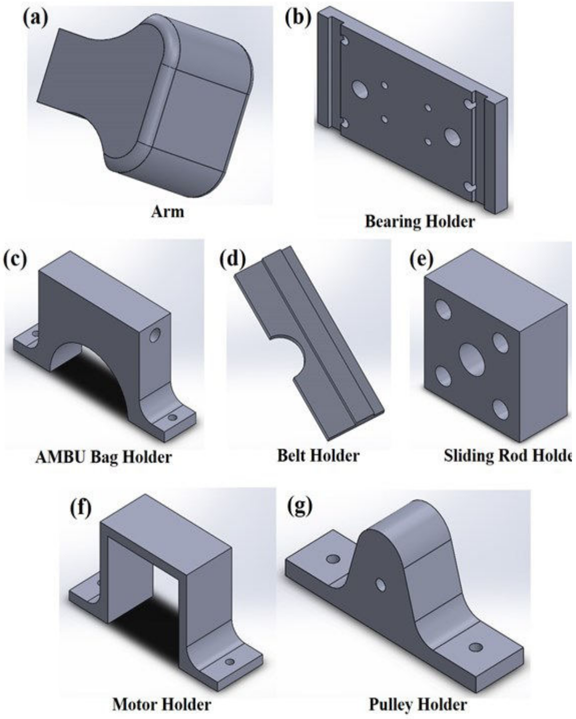


Fig. 1 3D models of various 3D printed parts used in the assembly.

manufacturing processes, making the system easy to scale. Additionally, the system is tested on a test lung to prove the medical efficacy of the proposed design.

II. METHOD OF PROTOTYPING

A. *Hardware*

1. *Mechanical System:*

The mechanical system is the concrete foundation of the device, where the actuation mechanism was driven using belt-drive systems. The whole mechanical system is comprised of two parts: Designing and manufacturing. The specialized parts like actuation arms, bearing holder, AMBU bag holder, belt holder, sliding rod holder, motor holder, pulley holder was first designed in Solid works, as shown in fig.1. Further parts had manufactured in-house by using Fused Deposition Modelling (FDM) based 3D printer. All the components used in the device are readily and cheaply available.

Readily available M8 screws are used for the assembly of various components. All the components are assembled inside wooden boxes (cheaply available and easy machining), which are assembled together using M8 screw rods. The actuating arms are also held using M8 screw rods. The actuating assembly consisting of the arm (Fig. 1a), arm holder, bearing holder (Fig. 1b), moves over M8 stainless steel rod using belts, powered using stepper motors. In the system, when one arm is moved from left to right, the other arm has to move from left to right (and vice-versa). To enable this, we attach the belt on opposite sides of the rod holders, enabling required linear transition even using one belt. The sliding rods are attached to wooden boxes using 3D printed joints (Fig. 1e), attached to wooden boxes using M4.8 nuts and bolts. The belts are supported by stepper motors and a pulley at the end to enable efficient linear actuation of the whole assembly. The motors and pulleys are also held to the system using a 3D printed motor holder (Fig. 1f) and pulley holder (Fig. 1g). During operation, the AMBU bag is pushed and released simultaneously, but the AMBU bag itself should remain fixed to ensure efficient energy transfer from arms to bag, enabling airflow. To keep the AMBU bag in one place, we designed an AMBU bag holder (Fig. 1c), which is held onto box holding rods.

2. *Electrical system*

The electrical system is the brain and heart of the device, where it is further classified into two parts: hardware and software along with its GUI interface. The following components had been used for smooth device operation: motor driver, stepper motor, pressure sensor, Arduino Uno, jetson nano, LCD touch screen, power supply, and ultrasonic sensor respectively as shown in fig.2.

a. *Motors*

The primary task for the electrical system is to drive the arms at the desired speed and up to the desired position to achieve accurate pressure curves required for clinically defined pressure mode. The mechanical design has both arms mounted on a belt drive that is driven by four stepper motors (NEMA-17, 4.2 kg-cm torque). By employing two BTS 7960 H-Bridge drivers we can excite 4 coupled coils together. The popular and easily available Arduino Uno board with an ATMEGA128 microcontroller is used to excite the four coupled coils of the stepper motors.

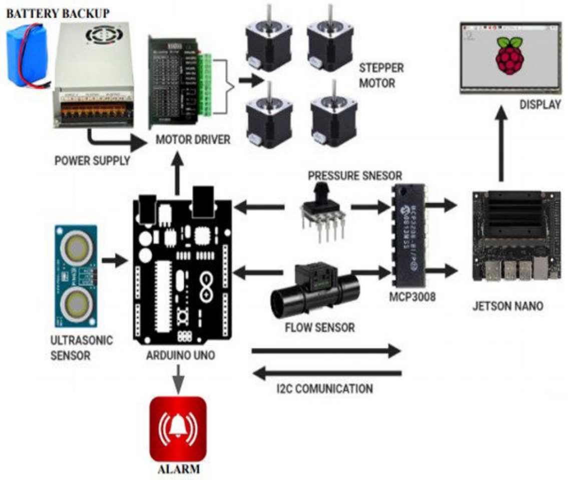


Fig. 2 Schematic diagram of used electronic components.

b. Sensor

We are using two sensors for the desired operation.

1. Ultrasonic Sensor: The ultrasonic sensor is used to auto home the arms. When the ventilator starts, the arm positions are unknown to the machine. And during continuous operation, even mild errors on positioning of arms can accumulate over multiple cycles of operation that can lead to arms moving slowly out of desired positioning.

2. Pressure sensor: Pressure is an important parameter of a ventilator system. We are employing a semiconductor base pressure sensor (SSCDAND005PGAA5). Here, we are mounting the pressure sensor directly onto the HEM filter which is situated near the mouth of the patient (to ensure accurate pressure measurement). The voltage to pressure conversion relation is given by equation (1).

$$v = \frac{.8 \times V_{supply}}{P_{max}-P_{min}} \times (P_{max} - P_{min}) + .1 \qquad (1)$$

c. Processor (Arduino Uno & Jetson Nano)

We are using two processors for the control of the system. The microcontroller board - Arduino Uno and the single-board Linux computer - Raspberry Pi. All operations have been controlled and drove by the microcontroller.

d. SMPS

The SMPS is the power source of the device integrated with the battery system. The SMPS is being kept inside the enclosure of the device and it is very handy and compact. The battery (10400mAh) system provides a power backup of approximately 30 minutes.

e. Enclosure design

The enclosure was primarily constructed using sturdy Plywood of 19 mm thickness. It has a slanted face in front where the 7-inch LCD is fixed. The reset button and the alarms also go in this face. The delivery tube of the ventilator comes out from the front panel. The back panel houses the power socket and power switch. This back panel is locked by a magnetic attachment and can be easily opened by pulling it. Moreover, the compact design of AARMED makes it weigh very less enabling easy transportation of the entire assembly.

B. Software & Graphical-User interface (GUI)

For precise control of pressure mode here we have developed an algorithm shown in Fig. 3. The interface provides clinicians a better visualization through which they can control all the necessary parameters such as BPM, Pressure, PEEP, etc. The programmable code is made such that it can sense all the required inputs given by the user and it responds accordingly. The GUI has been synchronized with microcontroller of the device. The flow order is first user (clinicians) can provide the inputs as per the patient condition, after which the system will check the home position of the arm of the ventilator. If condition is true with the set reference it will go to home position else it checks the current pressure with threshold pressure and time. Therefore, next step will be the inflation of insufflator by the mechanical arms. After that the current pressure is compared with threshold pressure and if it is less than threshold pressure it will continuously compress the insufflator value as fast as possible to meet the threshold pressure, simultaneously checks the inhale time condition if time is not completed then hold the pressure up to inhale time and this process is continue until inhale time is completed. If inhale time is completed then decompress the insufflator and reset the time clock and this cycle is completed until the stop command is given by user.

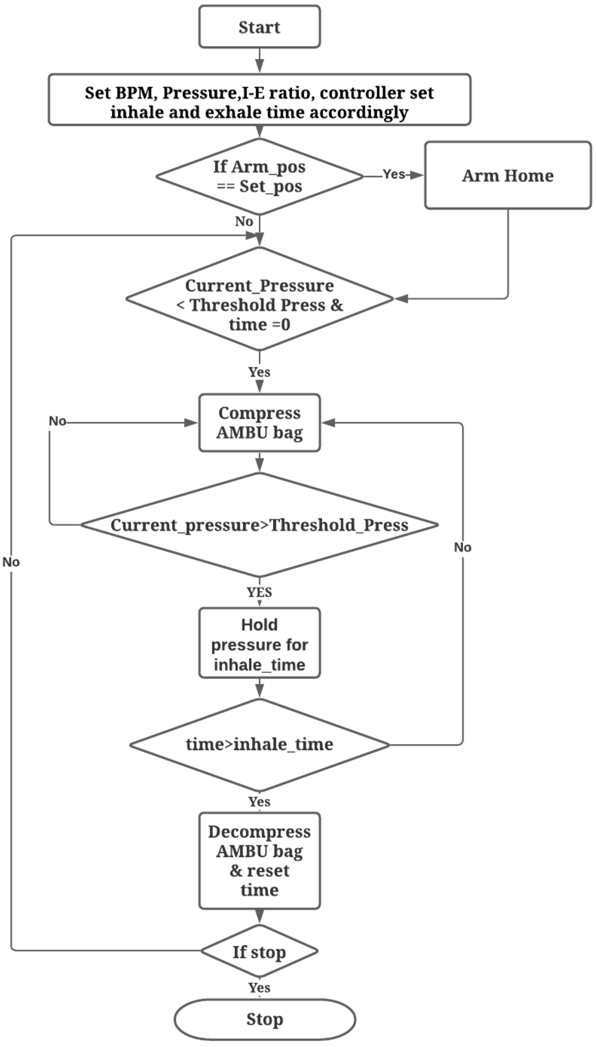


Fig. 3 Flow chart of the developed algorithm.

A user-friendly GUI has been developed using the TKINTER library using open-source python shown in fig 4. Soft controls have been integrated with touchscreen to control various system parameters. All parameters are

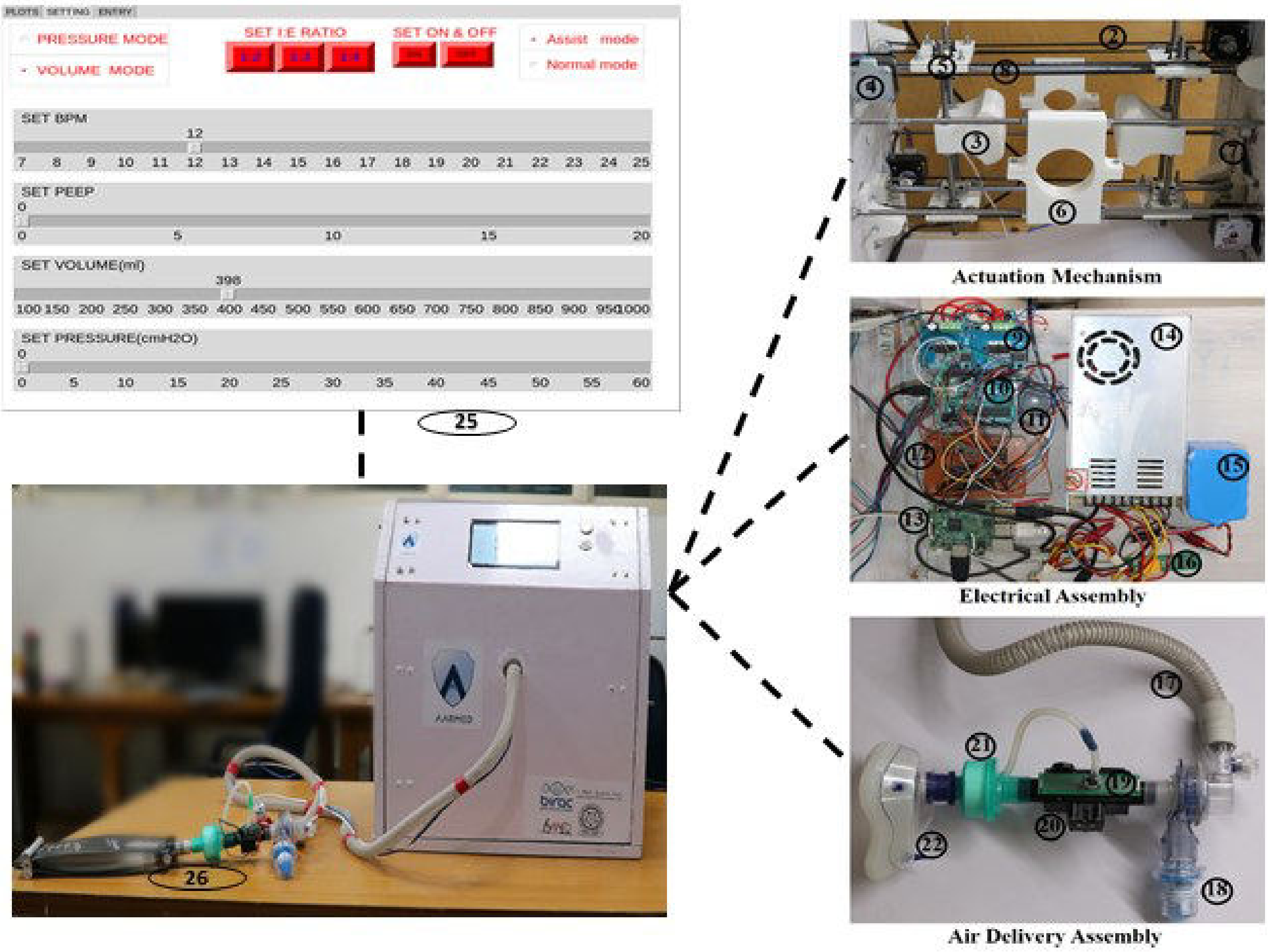


Fig. 4 Device design and assembly, showing various components used in actuation, electrical assembly, and air delivery system. 1) LCD Display, 2) belts, 3) push arm, 4) stepper motor, 5) rod holder, 6) AMBU holder, 7) position sensor, 8) holding rod, 9) motor drivers, 10) Arduino Uno, 11) alarms, 12) connection board, 13) raspberry pi, 14) power supply, 15) Li-ion battery, 16) relay, 17) air pipe, 18) PEEP valve, 19) pressure sensor, 20) flow sensor, 21) HEPA filter, 22) mask, 23) emergency stop/reset button, 24) alarm button 25) inset view of GUI and 26) test lung

shown to a single user interface. Different functionalities have been discussed below

III. GUI OPERATIONS AND THEIR USE

Breaths per minute (BPM): Normal humans breathe within the range of 12-20 BPM. However, in medical situations, this may need to change to control the amount of air/oxygen delivered to the patient for their treatment. Keeping this in mind, we have provided a wide range of precisely controllable BPM, from 7-25 BPM. This enables clinicians to precisely control the breathing rate, to meet the treatment requirements.

Inhalation: Exhalation (I:E) ratio: Another important parameter many times neglected in recent low-cost ventilators is the I:E ratio which is the ratio of time between inhalation and exhalation. AARMED has been programmed to give the user an option between three common I: E ratios namely "1:2", "1:3, and "1:4". Moreover, the required I: E ratio can be achieved in all the developed modes of operation (volume, pressure and assist mode).

Pressure: The air delivery to the patient should be done at optimum pressures to ensure no damage has been imparted to the patient's lungs. The pressure values are decided by trained clinicians, to ensure the safety of the patient. Our system can deliver air with a wide range of pressures, ranging within 5-60 cmH_2O. In addition, positive end-expiratory pressure (PEEP) can be precisely tuned from 5-20 cmH_2O, to maintain a minimum amount of pressure inside the lungs to avoid lung shrinkage.

Table 1. *Brief outline of system capabilities.*

Function	Capability
Device operation	Pressure-controlled mode
BPM	7-25
I/E	1:2, 1:3, 1:4
PEEP	5-20 cmH_2O
PIP	Up to 60 cmH_2O

IV. RESULTS

System features.

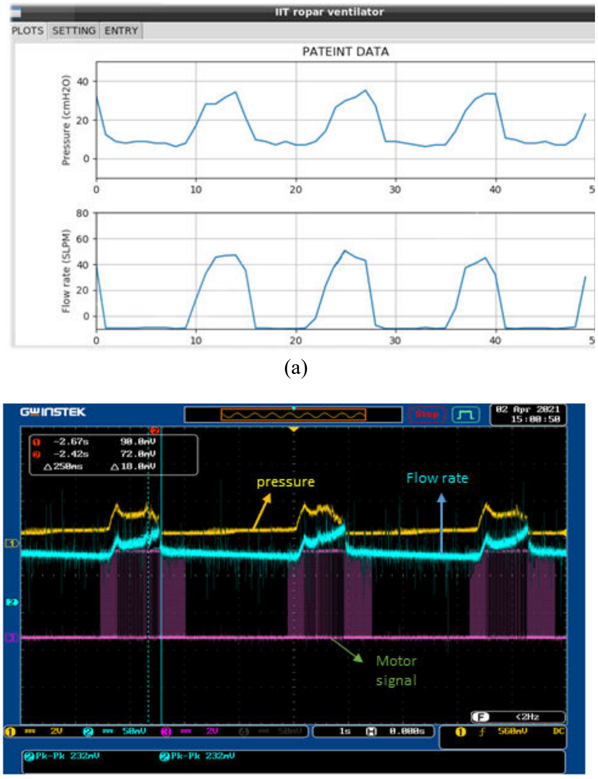
All mechanical ventilators need to fulfill some basic requirements to be useful as an alternative to conventional ventilator systems. These include the capacity of the system to operate within a wide range of breaths per minute (BPM), inhalation-exhalation ratios, tidal volume, pressure, and fraction of inspired oxygen (FiO2) percentages. The system capabilities have been briefly outlined in Table 1 and are described below in detail:

Workability of the device.

The device is currently working with pressure mode, the overall look and the inset view of GUI interface with consist of all control parameters are shown in Fig. 4.

Here in, a pressure threshold is entered by the doctor. Ventilator tries to reach that pressure at the beginning of inhalation as soon as possible. Once the pressure is reached, the ventilator tries to maintain this constant pressure till the end of the inhalation time by modulating the speed of bag compression. The exhalation is again patient controlled. This mode has now been enabled in AARMED. The user has to enter some prerequisite values of the desired breaths per minute (BPM), I:E ratio and pressure to be achieved during breathing. For achieving this stepper motors are intelligently controlled by using feedback from the pressure sensor placed near the mouth of the patient.

Fig. 5, depicts the temporal evolution of pressure and volume under the set parameters (Pressure: 20 cm H2O, I:E: 1:2, BPM: 20). In the DSO image, it can be clearly seen that the time lapse between each cycle is 5 sec, which turns out to be equivalent to setting parameter values. This shows the efficacy of the system, as set value is equal to the calculated value. In addition, DSO image (Fig. 5b) shows the presence of motor signals as the time of rise of pressure and as pressure start dropping. This shows that motors give signal as soon as pressure has to increase or decrease, as these are the moments where the motor has to start or stop compressing the AMBU resuscitator. Also, the real-time LCD snapshots have been shown (Fig. 5a), which closely matches with the DSO image.



(a)

(b)

Fig. 5 (a) Operational GUI interface of the device. (b) Hardware tested, and displayed by using DSO

CONCLUSION

Robust operation of AARMED is demosntrated which shows promising results while opearting in pressure mode. The low-cost, easy to assemble and scalable mechanical ventilator can thus serve as viable replacement for costly ventilators. Till date, graphical inteface(GUI) has been fully developed for all modes like assist, normal, pressure, and volume. The proposed design shows favourable results on artificial lungs. In future, we will be working on volume mode compatible with assist control mode.

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