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Design and Analysis of Ventilation System for COVID Patients

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ABSTRACT:-

Due to shortages of critical equipment, like ventilators, causing spikes in mortality rates during COVID-19 threatens to medical infrastructure at the regional level. Mass distributed manufacturing of ventilators has the potential to overcome medical supply shortages with the latest development and widespread deployment of small-scale manufacturing technologies like 3-D printers and open source microcontrollers. In this dissertation, a background on ventilators is provided with the reviewed literature to find the existing, examined designs for ventilators systems. With the considerably larger motivation of an ongoing pandemic, it is assumed this dissertation will garner greater attention and resources to make significant progress to reach a functional and easily-replicated ventilator system. In this dissertation work various techniques are identified for simulation of functionality tests of ventilation system for covid patients. Various parameters are identified and studied in this dissertation which are necessary to be considered in design of ventilation system. Different designs of ventilation system are modelled in this dissertation work by incorporating various essential parameters. The modeled ventilation system designs are evaluated in this dissertation work. Future work needed to move ventilators up to the level considered scientific grade equipment and to reach medical-grade hardware. Future work is needed to achieve mechanisms for the development and testing of ventilators for both the current COVID-19 pandemic as well as for future pandemics.

Keywords- Covid, Critical Equipment, Pandemic, Respiratory Diseases, Ventilator.

01. Introduction

In Coronavirus (SARS-CoV-2) causing coronavirus disease 2019 (COVID-19), and it's mutant, named "VUI202012/01", includes a genetic mutation in the "spike" protein that could be the cause of immediate and easy spread of the virus amongst people, are in part so dangerous because it threatens to overwhelm our medical infrastructure at the regional level, causing spikes in mortality rates [1–4].

Within the medical infrastructure, there are critical technologies that are generally available, but simply do not exist in a high enough density to handle the excessive volume of patients associated with pandemics.

The current medical system relies exclusively on specialized, proprietary, mass-manufactured ventilators from a small selection of suppliers. This supply model clearly fails when there is a sudden surge in demand for a relatively low volume specialty product such as ventilators in a pandemic as analyzed here. The vast majority of medical equipment is heavily patented by a few specialty medical firms that sell small volumes because during 'normal' times, a medium-sized hospital only needs a handful. These firms have historically aggressively protected their intellectual monopolies to the detriment of human lives.

In this paper, a background on ventilators is provided with the reviewed literature to find the existing, examined designs for ventilators systems. With the considerably larger motivation of an ongoing pandemic, it is assumed this dissertation will garner greater attention and resources to make significant progress to reach a functional and easily-replicated ventilator system. In this paper various techniques are identified for simulation of functionality tests of ventilation system for covid patients. Various parameters are identified and studied in this work which are necessary to be considered in design of ventilation system. Different designs of ventilation system are modelled in this work by incorporating various essential parameters. The modeled ventilation system designs are evaluated in this paper.

02. Literature Review

Coronavirus Disease 2019 (COVID-19) threatens to overwhelm our medical infrastructure at the regional level causing spikes in mortality rates because of shortages of critical equipment, like ventilators. Fortunately, with the recent development and widespread deployment of small-scale manufacturing technologies like RepRap-class 3-D printers and open source microcontrollers, mass distributed manufacturing of ventilators has the potential to overcome medical supply shortages. Respiratory diseases and failures are a major public health issue in both developed and developing countries. This global issue has been greatly accentuated by the COVID-19 pandemic, which has resulted in an urgent need for extra ventilators [5]. Even developed countries such as Spain, Italy, and the United States are suffering from a shortage of these expensive respiratory devices which also require a relatively long time to manufacture them [6]. This chapter describes various types of devices, existing available ventilators and open source ventilators.

There are two types of ventilator devices. One type simply pushes a certain volume of air into the lungs mechanically without accounting for whether the patient wants to draw air into their body or to push air out. Almost all of these devices are based on the use of the conventional bag valve mask (BVM) [7]. A BVM is a plastic bag that a clinical care practitioner can deflate manually with their hands, and therefore provides an inexpensive and easy way to force air into the lungs. Indeed, BVMs are applied by first responders to patients who are not breathing, rather than performing mouth-to-mouth resuscitation. All ventilator devices based on a BVM are essentially robotic arms that squeeze the bag again and again at a set frequency. These devices can be manufactured quickly and in large numbers, but since these ventilators are simply pumps that force air into the patient's lungs, they can only be used for patients under general anesthesia or those who are near death and have nonfunctional lungs. Applying such a device to a conscious patient would lead to a risk of death through barotrauma, which occurs when the human body is exposed to an inappropriate air pressure [8].

The second type of ventilator is more advanced. These devices are currently being used in resuscitation units to treat COVID-19 (and other) patients, as these ventilators are intelligent enough to be able to discern if the patient wants to draw in air or push it out and then help the patient to achieve the desired action [9]. A ventilator of this type has many sensors that interact with the human body, and air is supplied deliberately and accurately to the patient based on the sensor data. As an example, the Puritan Bennett 980 mechanical ventilator, which is a top of the line high-performance ventilator, provides advanced synchrony tools to help the clinician to set the ventilator to adapt to each patient's individual needs and thus provide the appropriate level of support throughout the breath [10]. However, such devices are very complicated pieces of machinery, making them very expensive and time-consuming to manufacture in large quantities.

03. Proposed Model and Conceptual Design

Patient management during COVID-19 faces serious issues of lung damage, and the ventilators must be able to handle situations of rapidly changing lung compliance, and potential collapse and consolidation. Thus as a general concern for any ventilator design the driving pressure of the ventilator is a crucial factor for patient comforts. In this section modes of operation of ventilators are described. This section also describes ventilator's conceptual design, control and user interfaces.

In particular, when a low tidal volume is used, the driving pressure is an important variable to monitor to assess the risk of hospital mortality. In light of the extreme importance of the pressure monitoring, the ventilator will target pressure controlled modes. This will include: PRVC (Pressure Regulated Volume Control) mode, SIMV-PC (Synchronised Intermittent Mandatory Ventilation); and in addition a basic mode of operation: CPAP (Continuous Positive Airway Pressure). The ventilator design also provides PEEP (Positive End-Expiratory Pressure), which is not a ventilatory mode in

itself but is designed to support steady low positive pressure to the lungs. The PRVC mode, which is standard for commercial ventilators, aims to set the tidal volume at the lowest possible airway pressure. In the case where the tidal volume is not achieved at a particular pressure setting, due to changes in the patient's airway resistance or lung compliance; this can then be gradually adjusted. SIMV-PC mode will allow the patient to take spontaneous breaths, and will assist the breathing when the spontaneous breath is taken. This mode uses an additional sensor for the detection of the negative pressure initiated by the patient breath. If the patient respiratory rate does not achieve the target value, additional mechanical ventilation is provided by the unit.

The conceptual layout of the ventilator system is described in this section. The targeted modes of operation are principally PRVC, SIMV-PC and CPAP. The design has the patient safety built-in as a priority, so that all failure modes revert to a situation which prioritizes patient safety. In particular, if the patient stops breathing in pressure support mode, the ventilator fail-safes automatically onto mandatory ventilation. The conceptual schematic is shown in figure 1.

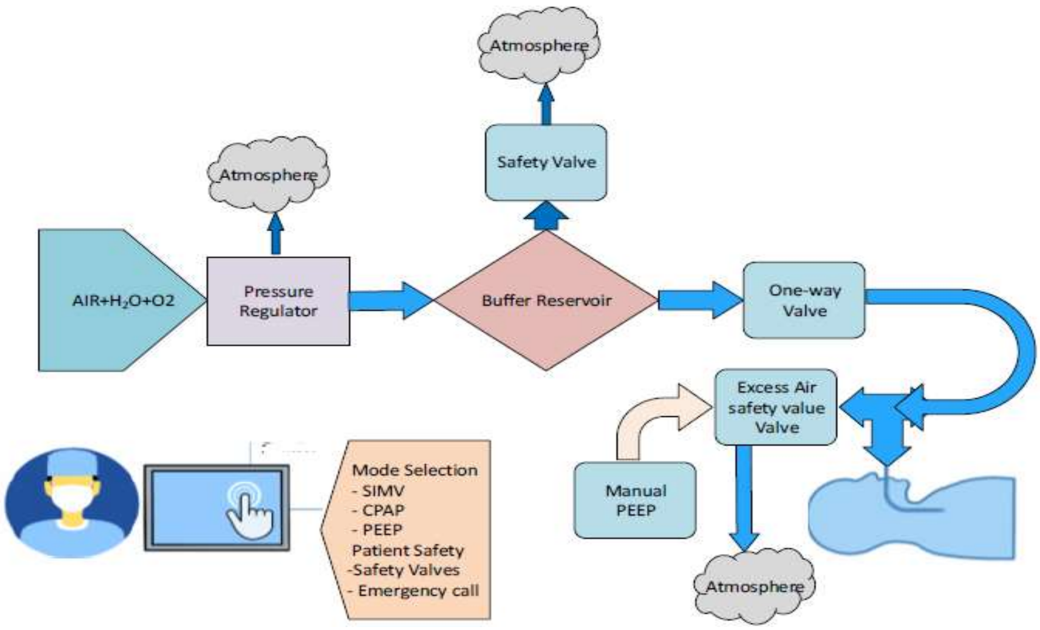

Figure 1: Conceptual Design of Ventilator.

The conceptual ventilator system can be designed with the following specifications:

- Working Pressure: Up to 50 cm H_2O.
- PRVC peak pressure limit set to 35 cm H_2O by default with an option to increase this in exceptional circumstances and by positive decision and action by the user.
- Operation modes: PRVC, SIMV-PC, CPAP.
- Exhaust mode: PEEP available with a set range between 0 and 5 cm H_2O.
- Minute volume flow capability: Up to 20 liters/min.
- Inspiratory flow capability: Up to 120 liters/min.
- Respiratory rate: 10-30 breaths/min.
- Inspiratory: Expiratory ratio; 1:2 will be provided as standard, and the unit will be adjustable in the range 1:1-1:3.
- Tidal volume setting to be provided in the range 250-800 ml in steps of 50 ml.
- Gas and Power Supply Inlet: Set according to the standard

The control concept, based around the embedded controller receiving the signals from the sensors and valves, and the touchscreen interface to the clinician, is illustrated in figure 2. The user interface can consist of an intuitive panel which displays the needed information and controls in a dynamic and continuous fashion. The controls and alarms described here are extremely preliminary and simply give an idea of the system functionality. The finalized list can emerge during the prototyping stages.

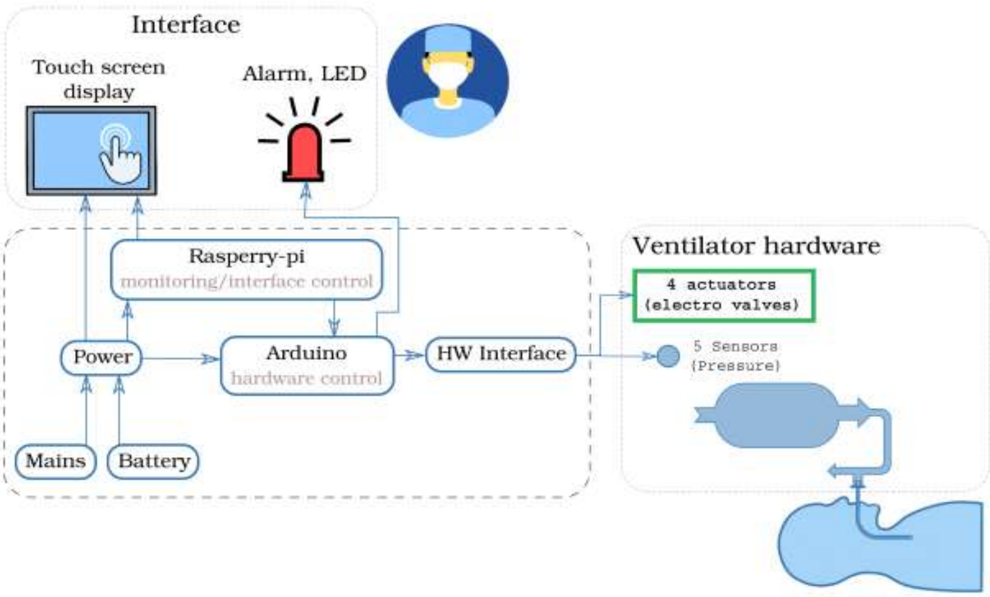

Figure 2: Generalized Conceptual Hardware Layout Comprising Controls and Interface Modules.

04. Ventilator Design Models

Dassault Systemes Solidworks Premium 2020 dramatically improve the way you develop and manufacture products. As the foundation for the entire SOLIDWORKS suite of product development solutions, SOLIDWORKS CAD packages cover design, simulation, cost estimation, manufacturability checks, CAM, sustainable design, and data management. Solidworks comes in Standard, Professional, and Premium distributions.

The designed automatic ambubag is shows in figure 3. It comprises various components and parts designed by using the solidworks library.

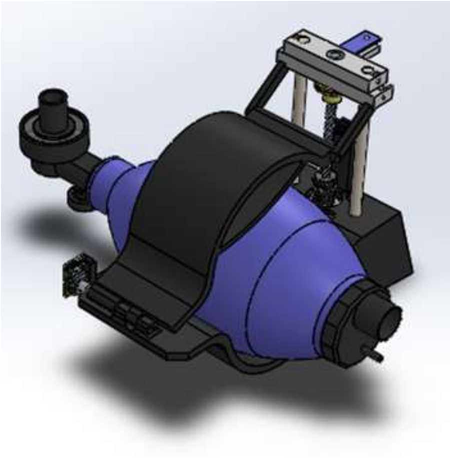

Figure 3: The designed Automatic Ambubag.

The designed mechnical ambubag is shows in figure 4. It comprises various components and parts designed by using the solidworks library. The components used for designing of mechanical ambubag are arm 2.1, User Library-SK8UU LINEAR GUIDE RAILS, ambu bag, nema 17, GT2_20T, left part, Leg, down component, Belt2-9, Nema17 Lbeugel, right component, an up subassembly.

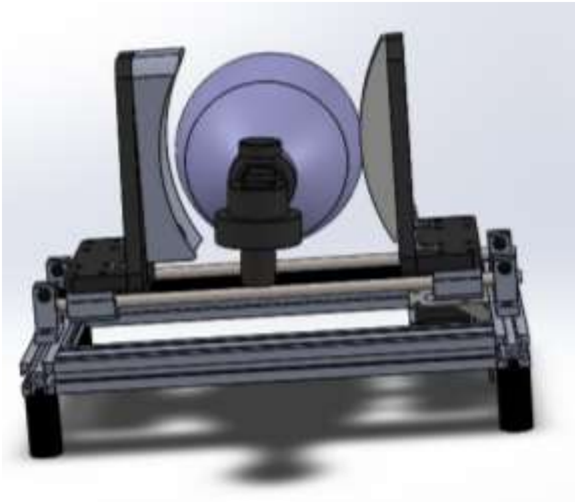

Figure 4: The designed Mechanical Ambubag.

The designed ensemble ambubag is shows in figure 5. It comprises various components and parts designed by using the solidworks library.

Figure 5: The designed Ensemble Ambubag.

The components used for designing of ensemble ambubag are Clamper Crank Link B, Clamper Frame, Clamper Crank Link A, Clamper Face, and Clamper Side. The ensemble ambubag can be modified to design and embedded ensemble ambubag as shown in figure 6. The required ventilation parameters can be set by using various encoder parts. Table 1 shows the classification of the total number of components in the designed assembly.

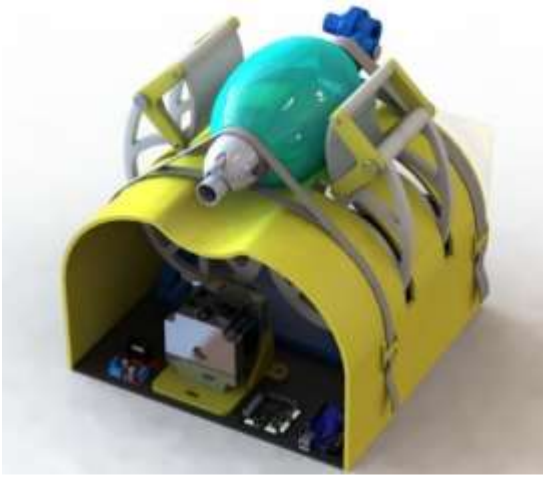

Figure 6: An Embedded Ensemble Ambubag.

Table 1: Component Statistics in the Designed Ensemble Ambubag

Total Number of Components in Assembly:		33
Parts:	Part Components:	33
	Unique Part Files:	13
	Unique Part Configurations:	12
	Number Of Bodies:	28
Subassemblies:	Subassembly Components:	0
	Unique Subassembly Configurations:	0
	Unique Subassembly Files:	0
Components:	Resolved:	8
	Number Of Top Level Components:	33
	Suppressed Components:	5
	Resolved Components:	28
Assembly:	Maximum Depth:	1
	Number Of Total Evaluated Mates:	62
	Top Level Mates:	73
	Flexible Subassembly Mates:	0

05. Results and Analysis

In Mass properties of automatic ambubag the coordinate system is used. The center of mass and the moments of inertia are output in the coordinate system of assembly of automatic ambubag. Table 2 shows the overall mass properties of the automatic ambubag assembly.

Table 2: Mass Properties of the Automatic Ambubag Assembly

Mass	14034.87 grams		
Volume	2171033.17 cubic millimeters		
Surface area	292499.80 square millimeters		
Center of mass: (millimeters)	X	11.64	
	Y	121.24	
	Z	259.50	
Principal axes of inertia and principal moments of inertia: (grams * square millimeters) Taken at the center of mass	Ix = (1.00, -0.02, -0.01)	Px = 24655674.02	
	Iy = (0.00, 0.07, -1.00)	Py = 58667223.44	
	Iz = (0.02, 1.00, 0.07)	Pz = 61684678.08	
Moments of inertia: (grams * square millimeters) Taken at the center of mass and aligned with the output coordinate system	Lxx=24667928.57	Lxy = -646616.75	Lxz = -183729.24
	Lyx = -646616.75	Lyy= 61660209.1	Lyz = -195733.68
	Lzx = -183729.24	Lzy = -195733.68	Lzz=58679437.92
	Ixx=1176079034.54	Ixy=19152390.78	Ixz=42192131.53

Moments of inertia: (grams * square millimeters) Taken at the output coordinate system	Iyx=19152390.78	Iyy=1008658314.92	Iyz=441376510.58
	Izx=42192131.53	Izy=441376510.58	Izz=266892495.64

In Mass properties of mechanical ambubag the coordinate system is used. The center of mass and the moments of inertia are output in the coordinate system of assembly of mechanical ambubag. Table 3 shows the overall mass properties of the mechanical ambubag assembly.

Table 3: Mass Properties of the Mechanical Ambubag Assembly

Mass	14690.77 grams		
Volume	2735229.97 cubic millimeters		
Surface area	570967.93 square millimeters		
Center of mass: (millimeters)	X	247.00	
	Y	266.03	
	Z	237.60	
Principal axes of inertia and principal moments of inertia: (grams * square millimeters) Taken at the center of mass	Ix = (0.01, 0.03, 1.00)	Px = 41251141.86	
	Iy = (0.89, 0.46, -0.02)	Py = 68651753.26	
	Iz = (-0.46, 0.89, -0.02)	Pz = 73699883.97	
Moments of inertia: (grams * square millimeters) Taken at the center of mass and aligned with the output coordinate system	Lxx=69738496.54	Lxy = 2080453.47	Lxz = 138949.45
	Lyx = 2080453.47	Lyy= 72587992.16	Lyz = 863419.39
	Lzx = 138949.45	Lzy = 863419.39	Lzz=41276290.38
Moments of inertia: (grams * square millimeters) Taken at the output coordinate system	Ixx=1938787919.90	Ixy=967398424.51	Ixz=862307180.10
	Iyx=967398424.51	Iyy=1798221972.82	Iyz=929452492.55
	Izx=862307180.10	Izy=929452492.55	Izz=1977231643.71

In Mass properties of ensemble ambubag the coordinate system is used. The center of mass and the moments of inertia are output in the coordinate system of assembly of ensemble ambubag. Table 4 shows the overall mass properties of the ensemble ambubag assembly.

Table 4: Mass Properties of the Ensemble Ambubag Assembly

Mass	1617.02 grams		
Volume	1617016.85 cubic millimeters		
Surface area	464880.97 square millimeters		
Center of mass: (millimeters)	X	122.69	
	Y	249.92	
	Z	359.94	
Principal axes of inertia and principal moments of inertia: (grams * square millimeters) Taken at the center of mass	Ix = (0.00, -0.04, 1.00)	Px = 16112648.54	
	Iy = (-0.01, -1.00, -0.04)	Py = 18803464.88	
	Iz = (1.00, -0.01, 0.00)	Pz = 30870804.95	
Moments of inertia: (grams * square millimeters) Taken at the center of mass and aligned with the output coordinate system	Lxx=30869001.16	Lxy = 143266.15	Lxz = 37685.42
	Lyx = 143266.15	Lyy= 18800310.98	Lyz = -114642.60
	Lzx = 37685.42	Lzy = -114642.60	Lzz=16117606.23
Moments of inertia: (grams * square millimeters) Taken at the output coordinate system	Ixx=341369616.97	Ixy=49728010.76	Ixz=71449909.64
	Iyx=49728010.76	Iyy=252641049.91	Iyz=145349501.06
	Izx=71449909.64	Izy=145349501.06	Izz=141462427.88

The designed models are compared on the basis of weight, estimated cost per assembly, and operations costs per assembly. The comparison is shows in table 5. The embedded ensemble ambubag and ventilator system can be used in the actual Covid-19 scenario for giving life support to the critical patients. Mechanical ambubag needs human intervention.

Table 5: Comparison of Designed Models on the basis of Cost and Weight per Assembly

Designed Model	**Weight (lb)**	**Component Cost (USD)**	**Operations Cost (USD)**	**Total Estimated Cost (USD)**
Automated Ambubag	37.33	551.47	0.14	551.6
Mechanical Ambubag	65.75	682.09	0.14	682.23
Embedded Ensemble Ambubag	26.48	561.53	0.13	561.66
Ventilator System	20.7	603.93	0.15	604.09

06. Conclusion

Ventilators are one of the critical equipment, unavailability of which can cause spikes in mortality rates during COVID-19. This dissertation work focused on presenting various designs for designing and manufacturing efficient ventilator systems. In this dissertation work four ventilator models has been designed namely automatic ambubag, mechanical ambubag, embedded ensemble ambubag and ventilator system. The Dassault Systemes Solidworks Premium 2020 is used for designing and analyzing the models. These models are compared on the basis of various parameters.

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