Remote Variable Monitoring App for Mechanical Ventilators Used in COVID-19

Carlos Miño¹, Omar Flor², Josué Quiroga³, and Andrés Cuaycal⁴

¹ Universidad Tecnológica Israel, Facultad de Ingeniería en Electrónica y Telecomunicaciones, Quito, Ecuador
   calolomino@gmail.com
² Universidad de las Américas, Facultad de Ingeniería y Ciencias Aplicadas, Ingeniería Industrial, Quito, Ecuador
   omar.flor@udla.edu.ec
³ Universidad Central del Ecuador, Facultad de Ciencias Médicas, Quito, Ecuador
   josueesteban_12@hotmail.com
⁴ Escuela Politécnica Nacional, Facultad de Ingeniería Eléctrica y Electrónica, Quito, Ecuador
   andres.cuaycal@epn.edu.ec

Abstract. In this article, the development and testing of an App that can be used to control and monitor parameters in mechanical ventilators in intensive care units is presented. Mechanical ventilation variables of a pressure-controlled ventilator are monitored and configured by the App with the use of a cellular device, wireless communication, and remote communication. The presented alternative improves the time response of intensivist specialists who are very demanded due to the COVID-19 pandemic. The use and performance of the developed App is demonstrated in a high-fidelity emerging mechanical ventilator.

Keywords: Remote monitoring · Emerging mechanical ventilator · COVID-19

1 Mechanical Ventilator

A mechanical ventilator is a medical equipment that assists a patient in case of Acute Respiratory Deficiency (ARD). It permits the proper support in inhalation and expiration in the most severe cases that occur by COVID-19 pandemic. The collapse of the respiratory system is a major complication that can be aided by a mechanical ventilator which helps in transporting air and oxygen to the patient’s lungs [1, 2].

Invasive-type mechanical medical ventilation equipment require that an endotracheal tube is inserted through a sedated patient oral cavity [3]. The inspiration is completely controlled by the ventilation mode, pressure, or volume. In order to maintain stable vital signs in a patient, the intensive care specialist determines the inspiration and expiration time. Therefore, the most adequate respiratory frequency (RR) is established considering the patient condition.

Mechanical ventilators allow the user to configure various parameters such as pressure and volume. Moreover, the user interface presents reference values which help...
monitoring the patient. Also, there are configurable alarms settings that are triggered when variations in reference values are detected [4, 5].

There are multiple mechanical ventilation modes. The most common modes are Controlled Ventilation (VC), Assisted Ventilation (AC), Pressure Support Ventilation (PSV) [6].

Controlled Ventilation (VC), is a method in which the ventilator controls the number of respiratory cycles by means of pressure or volume as a control parameter [7]. Given that the respiratory system is not able to perform the inspiration and expiration process. The ventilator regulates these processes and the intensivist specialist is the one who decides the respiratory rate, tidal volume or pressure according to the ventilation method [8, 9].

Figure 1 shows the internal design of the emergent mechanical ventilator SURKAN which was designed and fabricated in Ecuador. This ventilator is connected to an oxygen and medicinal air source to provide gas to the patient lungs using an Assisted/Controlled Pressure ventilation mode [10].

Components enumerated in Fig. 1 are: (1) Air and Oxygen Mixer, (2) Precision pressure regulator, (3) Pressure regulated valve, (4) Stepper motor NEMA 17, (5) inspiration manifold, (6) pressure and flow sensors, (7) oxygen sensor, (8) patient circuit, (9) patient respiratory system, (10) expiration manifold, (11) flow sensor, (12) solenoid valve, (13) HEPA Filter, (14) 12VDC Power supply, (15) main controller unit, (16) electric relays, and (17) controller board. Additionally, the implemented system requires a user interface that shows relevant information and should be ease of use.
2 Ventilation Parameters in Pressure Control Ventilation

There are two fundamental parameters that must be provided in mechanical ventilation: maximum pressure and plateau pressure. The first is reached when the ventilator provides air to the patient’s lungs, while the second is reached at the end of inspiration. In the operation, parameters that support the control and monitoring must also be included, such as Tidal Volume (TV), Respiratory Frequency (RR), Minute Volume (MV), Inspiratory Time (Ti), Inspiration/Expiration Ratio (I/E) [11].

The Tidal Volume (TV), is the amount of gas that the ventilator sends to the patient in each inspiration. Typically, a TV of 7–10 ml/kg is programmed (Except in neonates and patients with hypoxemic lung disease, in whom lower volumes are programmed). It must be considered that some respirators automatically compensate the volume of the tubing (Compression volume) and others do not, therefore, with the same programmed volume, the effective volume may be different [12].

The Respiratory Frequency (RR), or number of breaths per minute (bpm), administered by the ventilator, depends on the age and pathology of the patient. RR of 40–60 bpm are used in neonates, 30–40 bpm in infants, 20–30 bpm in children, 12–15 bpm in adolescents, and 8–14 bpm in adults.

The Minute Volume (MV) is the volume of gas that the respirator sends to the patient in each minute of ventilation. It is the product of the TD by the RR. The MV is the parameter that is most directly related to ventilation and, therefore, to the arterial pressure of carbon dioxide (PaCO2). In some ventilators the MV is programmed instead of the TV [12]. Therefore, to improve ventilation, it can be modified, depending on the patient’s condition, the parameters TV, RR or both.

The period of gas entry into the airway (tubulators, endotracheal tube, trachea, and bronchi) and lungs is known as Inspiratory Time (Ti). This parameter is programmed in both volume and pressure modes. In volume ventilation, inspiration is divided into 2 phases: In the first phase, gas enters (Ti) and in the second phase, the Inspiratory Pause Time (Tp), in which the air is distributed by the lung. In this phase the flow becomes 0. The inspiratory pause confirms that the ventilation is more homogeneous since it allows a redistribution of the gas through all the alveoli, even though they have different time constants (resistance and elasticity). In pressure ventilation, the Tp is not programmed [13].

The Inspiration/Expiration (I/E) ratio is the ratio of time spent on inspiration and expiration in each respiratory cycle. Usually an I/E ratio of 1/2 to 1/3 is used. The programming of the I/E ratio depends on the ventilator model. In some ventilators, the RR and the I/E ratio are programmed; in others, Ti and expiratory time in seconds; in others, the RR, Ti and Tp in percentage; and in others, RR and Ti in seconds [13].

3 Monitoring and Control Apps

Table 1 shows apps and software developed to monitor and control respiratory variables in mechanical medical equipment utilized in ICUs. The app name, developers and compatibility with cell phones, tablets, or computers [14–21].

The latter apps are developed to be used in commercial specialized equipment and allow the control of respiratory variables in invasive and non-invasive medical equipment.
However, these apps can not be implemented in a emerging mechanical ventilator due to the exclusivity and privacy of commercial apps. Many of these specialized apps were

**Table 1.** Apps utilized in invasive and non-invasive mechanical ventilators

| Applicative               | Autor                              | Characteristics                                                                 | Cell phone | Tablet | PC |
|---------------------------|------------------------------------|-------------------------------------------------------------------------------|------------|--------|----|
| Guide to NIV              | Phillips                           | Free clinical application for professional training in Non- Invasive Mechanical ventilation | X          | X      |    |
| My VENT                   | Felip Miralles (Oxigen, Eurecat e IRB Lleida) | Controls pressure and volume in invasive mechanical ventilation and non-invasive | X          | X      |    |
| Aventho                   | Google play                        | Control and calculation of PEEP, pulmonary compliance, transairway pressure, CO2 correction in non-invasive ventilation | X          | X      |    |
| Ventilator mode map       | Google play                        | Gas exchange, pressure and lung volume monitoring in mechanical ventilators    | X          | X      |    |
| Hamilton-C6               | Hamilton medical                   | Monitoring of patient oxygenation and ventilation parameters and simulated blood gas | X          | X      | X  |
| VentilO                   | L’Institut universitaire de cardiologie et de pneumologie de Québec (IUCPQ) | Control of pressure, tidal volume and breathing speed                         | X          | X      |    |
| Mechanical Ventilation Advanced | Google play                           | High frequency control, basic and advanced ventilation modes, pressure and volume control | X          | X      |    |

*(continued)*
developed by Google and others. Many of them with the support of brands and world renown institutions.

4 User Interface Design

In order to design the user interface various aspects were considered such as: ease of use and parameter visualization in a single screen. Respiratory variables were taken based on intensivist experts and commercial ventilators. A dark color palette is considered to prevent visual fatigue for the user and discomfort for the patient.

The Human Machine Interface (HMI) utilized in the ventilator was developed using web technology by means of HTML5 and CSS3 and Javascript to give dynamism.

The implemented dynamic interface allows the real time screen refreshment without updating the web page. Also, AJAX in Javascript allows the communication between the backend and control to send and get data.

Web technology is very useful because the user interface can be used in multiple devices. The ventilator will work as a web server, that is, a hotspot can be created or a router can create a local network so multiples devices such as smartphones, tablets, or laptops can be connected and get remote control of the mechanical ventilator

**Table 2.** User interface design used in the emerging mechanical ventilator SURKAN

| Patient identification | Alarms | Ventilatory mode identification |
|------------------------|--------|--------------------------------|
| Parameter control:     |        |                                |
| - PIP                  |        | Sensed parameter viewer:       |
| - PEEP                 |        | - PIP                          |
| - FR                   |        | - Tidal volume                 |
| - Ti                   |        | - Minute volume                |
| - Inspiration pause    |        | - FR                           |
| - Trigger              |        | - FiO2                         |

Table 2 shows the user screen divided in sections such as: control parameters input, graphs, monitoring of main and secondary parameters, a section with multiple buttons to
configure the equipment. Through configuring options, the user can use the equipment in automatic mode and could also set variables.

Raspbian operating systems offers the possibility to implement a web server very easily by using the command `apt-get install apache2`. By executing the last command all necessary libraries are installed and a web service is created usually in the 80 port.

Once the installation is finished the user has access to the web server via its IP and can be remotely accessed within the same local network where the equipment is connected.

5 Control Algorithms

The implemented code was programmed in Python using multiprocessing.

In Fig. 2, there are 4 processes. The main process that ran all the processes that control the equipment. As sub-processes we have one that is in charge of acquiring data from the pressure, flow sensors incorporated in component (6), (11) and FiO2 (7) to be used in all processes, the second is in charge net of performing pressure control and the last one calculates references to the air volume in each breath.

![Block diagram of principal processes](image)

Fig. 2. Block diagram of principal processes

PIP is determined using Eq. 1, which provides a relation between the sensor in voltage (6) and the actual value of the measurement. Equation 1 has been obtained from a tabulation of sampled and compared data with a reference value.

\[
PIP = (21.743 \times \text{voltage}) - 3.8927
\]  

The algorithms presented in this section were of our own development and to provide adequate control of the mechanical ventilator variables.

As a first calculation the equipment gets from the control panel the frequency and inspiration time then calculate the numbers of cycles by minute must to execute including the expiration time as shown in Fig. 5.

Figure 3 presents the pseudo-code of the program that controls the PIP pressure. By using components (4) and (3) the equipment must provide in each ventilation a value previously set by the user to the patient (9). It consists of a conditional in which it is verified that there is a ventilation or cycle, then in a loop it is verified that everything runs while there is an inhalation and also the pressure (6) that is delivered to the patient is measured. Moreover, through a PID control the values for the proportional valve (3) are obtained until meeting the objective that is the set PIP. In addition, minimum pressure
read cycle state
read maximum_pressure
read minimum_pressure
if (cycle=1)
  while
    read pressure sensor voltage
    convert to pressure units (cmH₂O)
    if (read_pressure <= minimum_pressure) or
        (read_pressure >= maximum_pressure)
      pressure_alarm=1
    else
      pressure_alarm=0
    end if
    if (read_pressure >= 0) and (read_pressure <= 5)
      patient_circuit_alarm=1
    else
      patient_circuit_alarm=0
    end if
    error calculation between sensed and configured pressure
    control pid
    proportional valve on/off
  end while
end if

Fig. 3. PIP pressure control algorithm

read cycle state
if (cycle=0)
  while
    read pressure sensor voltage
    convert to pressure units (cmH₂O)
    error calculation between sensed and configured pressure
    if (read_pressure <= configured_pressure)
      expiratory valve off
    end if
  end while
end if

Fig. 4. PEEP pressure control algorithm

values are verified to determine a minimum pressure alarm. Furthermore, it is established whether the patient circuit is connected or not, all with component (6).

Figure 4 presents the pseudo code of the program that controls the PEEP pressure that must be provided to the patient (9) and that is configured by the user. The algorithm consists of a conditional that verifies that the equipment is in an operating state. Through a loop it is checked that it is in an expiration period and by means of the measured value of pressure (6) it is compared with that configured in the interface. When the condition that the measured value is less than or equal to the set value is fulfilled, then the expiration valve (12) will close. Therefore, the desired residual pressure will be left in the patient circuit (8).
RESPIRATORY FREQUENCY CONTROL ALGORITHM

| read respiratory_frequency |
| read inspiratory_time      |
| read inspiratory_pause     |
| cycle_time = respiratory_frequency / 60 |
| expiratory_time = cycle_time – inspiratory_time |
| if (inspiratory_pause>0) |
|   expiratory_time = inspiratory_time – inspiratory_pause |
| end if |

Fig. 5. Respiratory frequency control algorithm

Figure 6 presents the pseudo-code of the control for the start of a ventilation cycle by means of the trigger or trigger sensitivity that is configured by the user. By checking a cycle, the pressure obtained or measured (6) is compared with the Trigger value. If this value is less than or equal to the Trigger, it stops the expiratory cycle (12) and starts a new inspiration (3). In addition, breathing apnea and patient alarms are activated and will be visible and audible in the equipment. The time is taken to compare it with the apnea time set in the equipment and when this is fulfilled the ventilation cycle is restarted by the configured ventilation parameters, that is, frequency, and normal inspiration and expiration times. This is done until a new respiratory effort is obtained from the patient (9).

TRIGGER CONTROL ALGORITHM

| read cycle state |
| read trigger |
| read apnea_time |
| if (cycle=0) |
|   read pressure_sensor voltage |
|     convert to pressure units (cmH20) |
|     compare sensed and trigger pressure values |
|     if (sensed_pressure<=trigger_pressure) |
|       stop expiration cycle |
|       start inspiration cycle |
|       apnea=1 |
|       patient_breathing_alarm = 1 |
|       counting_time = 0 |
|     else |
|       counting_time |
|       if (counting_time=apnea) |
|         patient_breathing_alarm = 0 |
|         apnea = 0 |
|       end if |
|     end if |
| end if |

Fig. 6. Trigger control algorithm
6 Commutation System

A centralized communication system was developed with the Ethernet protocol or the IEEE 802.11 standard, the assignment of the equipment IP addresses is performed dynamically using DHCP (Dynamic Host Configuration Protocol). The main system or BackOffice is assigned by a fixed IP on the same network.

In each equipment, the mentioned IP is configured to send and receive data, with a transmission speed of 150 Mbps which is convenient to avoid delays in the visualization and control of each equipment.

Figure 7 presents a diagram of the communication network used for monitoring and control of various mechanical ventilation equipment using a PC and cell phone app. For the user to unequivocally control the desired computer, assigned IP addresses are used on each computer. All patient information is reflected on the interface.

7 User Interface

The user interface was developed and shown in a 14-in. touch screen with touch capacitive technology of the “ASUS” brand. The developed ventilator graphical interface consists of 4 blocks (Fig. 9): parameter settings and buttons (a), real-time monitoring (b), function configuration buttons (c) and graphs display (d). The interface allows setting and monitoring of parameters, while the electronic system performs the control and communication process with the screen.

Ventilator operation variables must be entered by the specialist who has assessed the patient’s condition and determined its optimal parameters.

Parameters settings are detailed as follows: PIP parameter is entered in the interface through the “PIP” option that allows the entry of values in a range 0 to 40 cmH2O. The pressure variable at the end of expiration is entered into the interface using the “PEEP” option and the parameter can be varied from 0 to 15 cm H2O. The respiratory frequency
parameter is entered into the interface using the “Frequency” option that allows values to be entered in a range from 0 to 30 bpm. The inspiratory time variable is entered into the interface using the “Ti” option and the parameter can be varied from 0 to 5 s in decimal steps. The inspiratory pause parameter is entered using the “Ti” option and the user can change the parameter in a range of 0 to 5 s. The trigger parameter is entered through the option in the interface “Trigger” and the user can vary the value in cm H2O.

The following buttons are used to control the mechanical ventilator settings. Pressing the “Start” button will cause the mechanical ventilator to begin cycling by sending the pre-programmed airflow. When the user presses the “Manual” button the ventilator will send an inspiration cycle to the patient. By pressing “events” button, the user will be able to access a record of all the ventilator actions. By pressing the “Ventilation Modes” button the user can select the “Pressure Controlled” and “Patient Assisted” modes.

Patient monitoring can be viewed on the developed interface using the following indicators: “Exp Tidal V” the expiratory tidal volume in ml, “I:E” indicates the inspirationexpiration ratio, “Exp V min” monitors the expiratory volume per minute in LPM, “PEEP” indicates the real-time value of expiratory pressure on exhalation in cm H2O, “Ti” shows the inspiratory time in seconds, “Compliance” is displayed on the interface in ml/cm H2O, “Te” displays the expiratory time in seconds, “Insp R” the inspiratory rate is displayed in cmH2O/LPM and finally “Vt/PCI” in units of ml/Kg.

In the last section of the screen the Pressure vs. Time graph is shown. Figure 8 shows the resulting interface design and the remote application for controlling the SURKAN mechanical ventilator.

Fig. 8. Graphic interface design to remotely control the SURKAN mechanical ventilator, the 4 sections that correspond to the distribution proposed in Fig. 2 are displayed.
8 Results

The app was developed and implemented in the SURKAN mechanical ventilator which was designed and fabricated in Ecuador. The ventilator offers most respiration parameters found in a commercial mechanical ventilator.

Multiple tests were performed including, parameter changing with response analyzing, delays, communication, ease of use. The last test was verified by an intensive care specialist.

The following steps need to be performed to properly control the app and its remote controlling feature: (1) Enter the local network (2) Pairing with the communication network and identification of the desired equipment, (3) Set the following variables: PIP, PEEP, Frequency, Ti, Insp Pause, Trigger, depending on the professional’s criteria; (4) Alarms setting. (5) Reading and monitoring of ventilatory parameters.

Remote monitoring is possible since the mechanical ventilator and the app are connected to the same network. Due to the high speed of data transmission and low latency in the network, the programmed and monitored changes in the mechanical ventilator will be shown in real time with an imperceptible delay.

The implemented app and interface provide advantages for the equipment user by avoiding physical presence and using a smartphone, tablet or computer. In addition, since the alarms have a limited physical range, this alternative allows to extend these signals and facilitate the timely action by the intensivist. In the case of a lack of personnel in health institutions, this technology multiplies the range of action of professionals and offers the possibility of digitizing information with the work and implementation of databases.

Users of the app can monitor the patient who is connected to the emergent mechanical ventilator, in this way the patient will have a better treatment and possible complications can be avoided due to the lack of intensive care physicians present. In addition, remote monitoring will save several resources and time. A timely action can save the life of the patient. Figure 9 shows the application working on the SURKAN emergent mechanical ventilator.

![Ecuadorian emergent mechanical ventilator running the designed control and monitoring app.](image)

Fig. 9. Ecuadorian emergent mechanical ventilator running the designed control and monitoring app.
9 Conclusions

The app was developed for the control of the SURKAN emergent mechanical ventilator, of Ecuadorian origin and can be replicated in equipment that has a controller board with network access and where a web server can be configured. The characteristics and functionality of this application allow the use and configuration of equipment to be implemented in intensive care units as an alternative to support in the COVID19 pandemic.

According to specialized personnel in the use of these devices, the layout and variables presented on the 15-in. screen are friendly, easy to interpret and visualize, allowing intuitive use.

The possibility of remote management that this application allows, reduces the response time of specialized personnel given the high demand for ventilators and specifically in the cases of patients who totally depend on the use of this equipment and require greater attention and care by intensive care doctors.

References

1. Gutierrez, F.: Ventilación mecánica. Acta Médica Peruana 28(2), 87–104 (2011)
2. Gutiérrez, F.: Dianogístico, Monitoreo y Soporte Inicial del Paciente con Insuficiencia Respiratoria Aguda. In: Simposio: “Atención Inicial Del Paciente Crítico Para No Especialistas” (Parte 1). Revista Acta Médica Peruana (2011)
3. Rodríguez, Y., Rodriguez, D., Monsalve, A., López, K., Arévalo, A.: Recomendaciones clínicas para la atención del paciente agudo y crítico con COVID-19 (2020)
4. Grace, K.: The Ventilador: selection of mechanical ventilators. Crit. Care Clin. 14(4), 563–580 (1988)
5. Farias, J.A., Alía, I., Retta, A., Olazarri, A., Fernández, A., Esteban, A.: An evaluation of extubation failure predictors in mechanically ventilated infants and children. Intensive Care Med. 28(6), 752–757 (2002)
6. Chavez, A., De la Cruz, R., Zaritsky, A.: Spontaneous breathing trial predicts successful extubation in infants and children. Pediatr Crit Care Med. 7(4), 324–328 (2006)
7. Reina, C.M.: Ventilación mecánica controlada y asistida y controlada. Sci. Direct 59, 82–85 (2003)
8. Jouvet, P., Farges, C., Hatzakis, G., Monir, A., Lesage, F., Dupic, L: Weaning children from mechanical ventilation with a computer-driven system (closed-loop protocol): a pilot study. Pediatr Crit Care Med. 8(5), 425–432 (2007)
9. Scopesi, F., Calevo, M.G., Rolfe, P., Arioni, C., Traggiai, C., Risso, F.M.: Volume targeted ventilation (volume guarantee) in the weaning phase of premature newborn infants. Pediatr Pulmonol. 42(10), 864–870 (2007)
10. Naranjo, C., Flor, O., Tapia, J., Flores, E., Coba, A., Chango, E.: Diseño de Ventilador Mecánico Emergente en Modo Asistido/Controlado y Espointáneo por Presión, Revista Universidad Ciencia y Tecnologia, 1(1), 130–137 (2020)
11. Lopez, J., Carrillo, A.: Ventilación mecánica: indicaciones, modalidades y programación y controles., Elsevier, 6(6), 321–329 (2008)
12. Shults, J., Martsma, J., Slutsky, S., Gajic, O.: What tidal volumes should be used in patients without acute lung Injury? ASA Publ. Anesthesiol. 106(6), 1226–1231 (2007)
13. Carrillo, A., Lopez, J.: Parameters of mechanical ventilation, National Library of medicine (2003)
14. World Diagnostic News. https://www.diagnosticsnews.com/empresas/28176-guide-to-niv-philips-estrena-app-para-formar-profesionales-en-ventilacion-mecanica. Accessed 28 Nov 2017
15. Centre Tecnologic de Catalunya. https://eurecat.org/es/aplicacion-telemecanica-controlar-terapias-ventilacion-mecanica-pacientes/. Accessed 7 Jun 2019
16. Google Play. https://play.google.com/store/apps/details?id=com.icc.orientacionmedica&hl=es_419. Accessed 18 Jun 2020
17. Google Play. https://play.google.com/store/apps/details?id=mandupress.ventilatormodemap&hl=es. Accessed 2 Aug 2016
18. Google Play. https://play.google.com/store/apps/details?id=com.HamiltonMedical.c6simulacion&hl=es_EC. Accessed 17 Dec 2019
19. Google Play. https://play.google.com/store/apps/details?id=ca.qc.iucpq.ventilo&hl=es. Accessed 14 Apr 2020
20. Google Play. https://play.google.com/store/apps/details?id=soooooonandroid.mechanicalventilationadvanced&hl=es_EC. Accessed 4 Oct 2018
21. Google Play. https://play.google.com/store/apps/details?id=com.ssafadi.vent_sim&hl=es_EC. Accessed 23 Sept 2019