INTELLIGENT ASSISTED/CONTROLLED MECHANICAL VENTILATION (A/C MV) AUTOMATION SYSTEM DESIGNED FOR AN EXPERIMENTAL ARTIFICIAL VENTILATION DEVICE

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Abstract - The article presented a supervisory command and control entity designated for a mechanical ventilator, that allows the medical personnel to monitor and control the main device used in an automated process. The entity is in fact an automation system, that is used for assisted/controlled mechanical ventilation of critically ill patients, for collecting information from multiple intelligent sensors, for supervising the process and then integrates this information to make it available for the medical personnel. Starting from this technology formulated concept, the article aims to develop and test a laboratory experimental demonstrator Assisted/Controlled Mechanical Ventilation (A/C MV) automation system for a mechanical ventilator that hosts a programmed human machine interface (HMI) application and a central processing unit which will be acting as the brain equipped with a developed control algorithm.

Keywords: Automation, Ventilation, Experimental, HMI Interface, Laboratory experimental demonstrator.

1. Introduction

Artificial ventilation is necessary in situations where a patient cannot, by his own natural means, support himself breathing function. Ventilation can also be performed if a patient has moderate respiratory failure or unilateral.

The lung, driven by the thoracic pressure, generated by the diaphragm, has the role of ensuring, through the alveoli, gas exchange (O2 and CO2) with the blood in order to maintain metabolic reactions, vital functions, optimal irrigation of muscular system and organs.

Respiratory failure can be caused by internal factors such as the accumulation of pulmonary mucosa, edema pulmonary, metabolic reactions of the alveoli from various gaseous compounds (chlorine, caustic soda, vapors from petroleum products, etc.) or by external factors such as falls from a height (falls from a height), chest traumas/injuries or viral and/or bacteriological infections that lead to pleurisy, etc. Viral infections can have dyspnea as the main signs which is manifested by heavy or jerky breathing.

The key issues addressed by this article, and hence open issues for research (also extensively documented in literature [1-21]) are safety and efficiency. These issues are critical factors to be considered, because of the very large number of parameters that need to be acquired with high sampling rates during the testing of the mechanical ventilator, via a multitude of sensors which transmit signals to the laboratory experimental demonstrator A/C MV automation system.[4]

“Patient safety: Identifying and managing complications of mechanical ventilation” displays the results achieved by a mechanical ventilator by improving safety, operability and reliability [2]. The paper is considered as a starting point from these results.

The starting point from which the article seeks to fulfill its purpose is the block diagram of the pulmonary ventilation device, with all its components, as described in figure 1.
Artificial ventilation machines use the hospital’s air and oxygen sources to mix them into a single gaseous compound that is controlled in terms of the following variables [1-21]:

- $V_T$ - Tidal Volume;
- $V$ - Injected mixture flow per inspiration;
- $P_{\text{peak}}$ - Instantaneous pressure at the peak of respiration;
- $P_{\text{plateau}}$ - Stagnation pressure at the peak of respiration;
- $IPAP$ - inspiratory positive airway pressure;
- $EPAP$ - expiratory positive airway pressure;
- $\text{FiO}_2$ - fraction of inspired oxygen;
- $\text{SaO}_2$ - saturated oxygen.

The elements used to achieve this are the respiratory rate and tidal volume or inspiratory pressure. If a targeted pressure mode is used, the pressure will be adjusted so that a certain tidal volume will be obtained. Other adjustable parameters are required such as PEEP and FiO2.[5], [6]

The project ventilation modes that were identified in literature [1-21] and were developed into the laboratory experimental demonstrator A/C MV automation system with their descriptions are as presented in the following table.

### Table 1: Description of ventilation modes

<table>
<thead>
<tr>
<th>Ventilation Mode</th>
<th>Start</th>
<th>Control</th>
<th>Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Assist Control</td>
<td>Sets the frequency or initiated by the</td>
<td>Flow (volume)</td>
<td>Volume or time</td>
</tr>
<tr>
<td></td>
<td>trigger of the patient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Assist Control</td>
<td>Sets the frequency or initiated by the</td>
<td>Pressure</td>
<td>Time</td>
</tr>
<tr>
<td></td>
<td>trigger of the patient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Support</td>
<td>Initiated by the trigger of the patient</td>
<td>Pressure</td>
<td>% from the peak of the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>flow</td>
</tr>
</tbody>
</table>

Volume Assist Control mode can have either a prescribed value for the frequency of the inspiration set by physician or the patient may trigger the start of inspiration. If this respirator trigger is missing, the laboratory experimental demonstrator A/C MV automation system delivers the preset mandatory frequency.

For the Volume Assist Control mode, the controlled variable is flow. Even if the total volume has been set, flow is the parameter targeted. When the targeted volume has been delivered by the predefined flow, inspiration is ended and the plateau phase reached. The plateau pressure can then be measured as a key medical parameter.

Pressure Assist Control mode has the same criteria for when inspiration is started, but it delivers a preset pressure and the tidal volume is a resultant based on lung compliance. It must be taken to account that a leak around the endotracheal tube or even some cardiac oscillations may trigger the A/C MV automation system, giving the impression that the patient is breathing, when that is not the case, so safety mechanism and adaptable pressure triggers need to be included.

Pressure Assist Control mode controls the pressure delivered by the system. It offers a variable flow, practically any flow that may be necessary to achieve that preset pressure. Once the pressure is achieved, inspiration is terminated, and expiration begins.

Pressure Support mode assists the respiratory efforts of the patient and so it decreases respiratory work. The criteria for the end of the respiratory cycle is based on a percentage from the peak of the flow as determined by spirometry readings from intelligent sensors.

The theoretical development which is a starting point for the central processing unit algorithm of the
laboratory experimental demonstrator A/C MV automation system is defined through the flow-time graph [7]:

![Flow-time graph](image)

Figure 2: Flow-time graph of the inspiratory/expiratory time, the starting point for central processing unit algorithm [8]

### 3. Methodology

The need for the development of this project started from the lack of pulmonary ventilators during the COVID-19 in the context of a number of patients who needed these devices in order to survive. Considering the research extensively documented in literature [1-21], an A/C MV automation requirements analysis for finding a solution which defines the automation architecture was performed. Also, a study, a selection of equipment options and development of an optimal solution for the completion of the AC automation hardware configuration that are best suited for the chosen A/C MV automation infrastructure were achieved. The next step was developing electrical diagrams of the interconnected hardware equipment which forms the architecture of A/C MV automation system according to the results obtained from the studies performed.

The next step was to achieve the A/C MV automation hardware execution and to configure the equipment to be ready for data communication.

It was necessary to perform an analysis on the available programming languages that can be used for fulfilling project scope. Taken into consideration that the CPU was integrated into a PLC chosen from a specific provider, Ladder diagram programming language was the only option suitable for the PLC. An application named Proficy Machine Edition given by the PLC and HMI provider, was used for the developing both, the PLC software and the HMI runtime application.

| Table 2: Programming language selection |
|-----------------|----------------|-----------------|
| Equipment       | Programming language | Programming environment |
| PLC – Emerson Versamax | Ladder diagram | Proficy Machine Edition v.9.8 |
| HMI – Emerson Quick Panel | Object programming | Proficy Machine Edition v.9.8 |

Also, the communication protocols that are declared in the HMI runtime application for the selected central processing unit were defined. A leading algorithm for the central processing unit was developed by programmers. The algorithm takes over tasks that are inputted from the HMI runtime application.

Once the software programming of the central processing unit and of the HMI has been developed, a test program of the laboratory experimental demonstrator A/C MV automation system was performed on an artificial lung that mimics critically ill patients to show the HMI runtime application functionality and optimization. This objective first had an impact on the project outcome by setting up a priority for experimental use of the algorithm. Secondly, the feasibility of the project was demonstrated when the laboratory experimental demonstrator A/C MV automation system was tested within the mechanical ventilator test bed. Experimentation was performed according to the test program resulted from this activity. Safety procedures implementation for the HMI runtime application and the central processing unit were determined. The laboratory experimental A/C MV automation system had ensured safety operation of all imposed functionalities.

Connectivity tests were performed on the hardware of the laboratory experimental A/C MV automation system. The limits of the communication system were also tested. A test program was followed during experimentation. Therefore, tests were performed on the HMI runtime application. Certain operating scenarios were developed during experimentation. HMI runtime application functionality and performance were analyzed according to the test program. Results were obtained by testing the central processing unit algorithm efficiency and having the laboratory experimental A/C MV automation system connected on a provided mechanical ventilator. Endurance tests were executed. Overload capability of the laboratory experimental A/C MV automation system was assessed. Unforeseen events like accidental start-up or emergency shutdown of the laboratory experimental A/C MV automation system were simulated.
A risk associated with project implementation has been identified in regard to the central processing unit algorithm performance, which could not operate at maximum potential at all programmed ventilation modes, and/or suffer from safety issues. A way to manage this problem is to perform a comprehensive and systematic study in regard to operation modes algorithms and identify all possible scenarios for safety issues.

Programming the HMI software application and the central processing unit algorithm could pose a risk that tasks will not be able to operate with the expected efficiency. Because of this, the performance of the laboratory experimental A/C MV automation system could be limited.

This risk was addressed through careful software design, software optimization and extensive testing on clinical models of artificial lungs.

4. Results and Discussion

A custom developed software allows an accurate and full control of the mechanical ventilator through the central processing unit. The laboratory experimental demonstrator A/C MV automation system communicate data through the central processing unit and the human-machine interface by using a defined compatible communication protocol.

As a first result of the project was the A/C MV automation system shown in figure 3.

The laboratory experimental demonstrator A/C MV automation system equipped with custom made software displays in real time the parameters from a mechanical ventilator test bed. The human-machine interface provides a communication with the A/C MV automation system operator through screens containing process flow diagrams, values for the parameters, states and processes commands with the mechanical ventilator central processing unit.

The software system within the laboratory experimental demonstrator A/C MV automation system includes a data acquisition, processing and recording system for the running parameters and states delivered by a central processing unit. A smart data acquisition procedure was implemented on the laboratory experimental demonstrator A/C MV automation system. The procedure generates data.
files for later interpretation and post-processing upon request. Post-processing of data is mainly performed manually by medical personnel and requires an enormous workload [9]. The current solution has the potential benefit of decreasing time spent reviewing data and hence increase time spend treating the patient.

Once the ventilation process has started, the HMI can track in real time the graphs that indicate the trend of vital parameters such as pressure, flow and gas volume inside the system. In the right side it displays values of pre-determined parameters from the process, like: the fraction of inspired oxygen (FiO2 [%]), the respiratory rate, the tidal volume, the positive pressure at the end of the expiration (PEEP [cm H2O]), the inspiratory pressure, the mean airway pressure (MAP) etc.

These measured values are being displayed in big numbers, on the side of the screen. Therefore, any pin-point variation, out of the normal range or lack of one or more parameters can be captured on the operator panel. Figure 4 and 5 is the display behind which the command and control algorithm is being executed during the ventilation process.

A degree of novelty was established by the fact that the laboratory experimental demonstrator A/C MV automation system has an increased custom developed algorithm efficiency for its central processing unit.

The figure 6 flowchart was used as a benchmark for the development of the PLC algorithm that the automation system used in order to make decisions in operation.

![Figure 5: Main working HMI screen in P_AIC mode of the laboratory experimental A/C MV automation system](image)

![Figure 6: The flowchart used for developing the algorithm of the experimental A/C MV automation system [8]](image)
The custom programmed application which runs on the HMI of the laboratory experimental demonstrator A/C MV automation system is a relevant result of this project. This HMI developed application brings novelty through the concept of one custom made software entity that is in charge to monitor and command the mechanical ventilator. Hence, this lowers the magnitude of change that must be performed by the medical staff during mechanical ventilation and such will improve care to patients, especially during a COVID-19 pandemic when shortage of medical personnel is the biggest problem worldwide [10]. These features will be developed in collaboration with intensive care physicians so that the standard of care is maintained along with patient safety.[11]

5. Conclusions

First objective of the project was to perform a requirements analysis in order to find a solution which defines the A/C MV automation architecture for the laboratory experimental demonstrator. This first step was crucial for the outcome of the project as it has a significant role in overall feasibility.

After the requirements analysis was completed, the second objective was to develop an equipment structure and set up its hardware configuration for the A/C MV automation system. The hardware configuration provided the optimal connectivity to the mechanical ventilator test bed. This step was also important for the purpose of establishing a high speed connection that will act as a support for the entire communication between the sensors of the mechanical ventilator test bed and the laboratory experimental demonstrator A/C MV automation system. The performance outcome and the feasibility of the project depends on the results from these first objectives and from the next one which are related to software implementation.

A central processing unit and a programming environment were selected for developing the algorithm which runs on the laboratory experimental demonstrator A/C MV automation system. For achieving this third objective, different solutions for the central processing unit and the programming environment were taken into consideration and a complex analysis was performed, after which the best feasible option was selected.

The fourth objective in this category was to perform an analysis in order to determine the best solution for the operating requirements of the HMI. Completing this objective assured the best support for optimal running of the developed application in a user-friendly, easy to use by medical stuff which is a significant project outcome.

A relevant objective for the project outcome was programming the central processing unit and the HMI application for the laboratory experimental demonstrator A/C MV automation system. After an inception developed version of the application software was developed, it was used for further improvement during the project, taken into account the system needs and efficiency. Certain programming techniques were used to implement advanced algorithms that increase calculation power of the central processing unit.

Algorithms were therefore developed and tested on the laboratory experimental demonstrator A/C MV automation system which is capable to associate tasks from the human machine interface like resources consuming data acquisition in real time and process calculation. During tests, the A/C MV automation system performed tasks to an artificial lung as it was programmed.

A significant challenge for the feasibility of the project was to establish a suitable communication protocol between the HMI interface and the central processing unit of the laboratory experimental A/C MV automation system.

The main outcome of the project was to operate the HMI interface during tests and to interpret the acquired data sets and comparing them to expected values predetermined by the medical staff. An analysis was also performed concerning the behavior of the laboratory experimental demonstrator A/C MV automation system when critical events, such as an emergency shutdown, occur.[12]

References

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