Design and Implementation of an Electronic System to Monitor Lung Re-Expansion Physiotherapy Processes

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***Abstract*—** This paper outlines the design and implementation of an electronic system that aims to monitor the Respiratory Flow and to estimate the Volume and Respiratory Rate of patients undergoing lung re-expansion physiotherapy. The followed design process was carried out considering a combination of the TRIZ and Design Thinking methodologies, who provide a comprehensive and integrated analysis that ensures that the solutions offered meet the needs of the users. Additionally, the implementation of the system was further supported through the application of Axiomatic Design and decision-making techniques such as the Analytic Hierarchy Process (AHP).

Besides, the development process consisted of three key stages, with a practical prototype approach taken in two of them and a theoretical proposal in last one. Thus, the first stage involved the creation of a prototype that could measure and display the physiological variables through a LabVIEW graphical interface, providing a visual representation of their behavior in a normal operating state. Subsequently, the second prototype processed the variables using a microcontroller system and incorporated Bluetooth wireless communication. The final approach of the project aimed to refine the estimation of Respiratory Flow by adapting the ISO 5167 model for orifice plate sensors, optimizing two of its critical flow behavior coefficients for medical applications.

Finally, it should be noted that this project has been developed within the framework of the research project *Respiratory incentive system for lung re-expansion in patients with sequelae of COVID-19*, which not only provided the necessary equipment for its execution, but also allowed a continuous collaboration through a multidisciplinary team that led to the achievement of results beyond expectations.

I. INTRODUCTION

Reduced respiratory capacity is common after surgical procedures or the affection of the respiratory system due to diseases, these conditions cause weaknesses or atrophies in the structures involved in the respiratory process, hindering the correct execution of this vital function. An adequate recovery process is then crucial to ensure a good quality of life of people and even more to not generate other conditions or complications in the health of the patient. Currently the recovery processes cover a variety of procedures among which stand out the lung re-expansion physiotherapies, which must be prescribed and supervised by a specialist. This type of procedure involves the medical prescription of a set of specific exercises that must be performed by the patient using specialized medical equipment. Most of the devices used to perform these procedures consist of a simple pneumatic principle, which only gives an idea of the patient's recovery evolution to the physiotherapist. With all the current technological development in the medical equipment, it comes to think about how to develop a system that can obtain a better estimation of the patient's condition and its progress in each physiotherapy, considering an environment in which the patient feels comfortable and motivated. Therefore, it has become necessary to implement an innovative medical instrumentation that accounts for the evolution of the patient's health status during a lung re-expansion physiotherapy process, providing more detailed information to physiotherapists of their respiratory health condition, considering that this will be developed in a gamification environment (within the framework of the research project) in order to incentive an active participation in the recovery process.

II. THEORETICAL BACKGROUND

Theory of Inventive Problem Solving (TRIZ)

Design methodology that allows an inventive approach to the solution of an engineering problem by providing a set of systematic techniques and axioms that help to determine the key features and aspects. TRIZ can be understood as a systematic methodology based on human-oriented knowledge for inventive problem solving [1]. Although the application of the theory does not provide a direct solution to solve the problem by itself, it does provide a structured path, which favors the generation of ideas aimed at the needs of the stakeholders.

The basis of the problem analysis proposed by TRIZ is framed in the identification of a Technical System (TS), that can be defined as a set of elements that takes energy from the outside and converts them to perform a Main Function on an object [2], the elements conforming the TS are Engine, Transmission, Working Tool, Control and Casing. Continuing with the methodology, TRIZ proposes a systemic analysis of the problem by means of a space-time decomposition called nine-window analysis, that results in the establishment of ideal attributes, which will be study through some contradictions that are extracted by analyzing in detail the transition between the present and future windows. These contradictions will be subjected to a *Contradiction Matrix*, that provides a set of parameters in conflict, leading to the establishment of TRIZ principles that give a foretaste of proposals for solving the problem adequately.

Design Thinking

It is Human-centered approach focused on the innovation, that together with a set of tools, allows identifying the indispensable needs of the people involved in a design problem [3]. Its application is fundamentally based on five stages: Immersion, Analysis and Synthesis, Ideation, Prototyping and Testing. Through these stages, the designer will be able to recognize the state of the problem, identifying the key factors, conducting a complete field analysis and being able to apply an iterative prototyping methodology to improve the design until the problem is completely and optimally solved [4]. Although its stages do not provide a step-by-step guide on how to solve the problem, they do provide useful tools for structuring a good solution.

Axiomatic Design

It is a methodology that provides the quality of understandability and transferability between people working within the framework of a project, it also provides clear criteria for decision-making that reduce subjectivity and contribute to the reduction of time for the generation of new products [5]. The fundamental axioms on which this methodology is based are functional independence to avoid couplings and redundancies of specific functions and minimum information content to determine the quality of the design product, where quality refers to the fulfillment and satisfaction of the proposed requirements.

Analytic Hierarchy Process (AHP)

Structured technique for making decisions involving multiple criteria, based on a nonlinear framework that allows several factors to be considered simultaneously, accompanying the process with numerical operations that permit synthesis or value conclusions to be reached and that, in turn, encompass the development of inductive and deductive thinking [6].

Physiotherapies for Lung Re-expansion Processes

They are intended to promote the re-habilitation of lung capacity and the reopening of the airways of patients undergoing sequelae, collapse, or atrophy due to respiratory diseases. Thereby, the common follow-up model for respiratory physiotherapies usually starts from the ventilatory deficiencies of each patient and allows them to improve their functional capacity and quality of life [7]. The prescription of the physiotherapies of pulmonary re-expansion are given under a rigorous evaluation of the patients by specialists, where consequently a physiotherapy process can be determined, that looks for the recovery of patient. This process must be continuously monitored by a physiotherapist, to study the condition of the patient, and usually consists in an adjust of the special exercises, which must be done in a certain number of sessions and series.

Orifice Plate Sensors

These sensors are widely used for flow measurement of liquids and gases, characterized for being simple and robust, low cost, having an acceptable accuracy and not requiring calibration [8]. Their principle of operation is based on the Bernoulli theorem, where there is a mathematical relationship between the differential surface pressure in a pipe before and after an obstruction and the flow through it. This type of flowmeter implements the flow obstruction through a perforated plate perpendicularly located inside a pipe. Most of the mathematical models proposed for the description of the flow and differential pressure relation vary depending on the geometrical distribution and the materials made of. The ISO 5167 standards [9] [10] provide a specialized industrial application model that relates the flow through this sensor and the differential pressure, considering different geometric and material factors, who follows the flow equation presented below.

$$Q_v = \frac{C\epsilon}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

$$\mathrm{C} = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521\left(\frac{10^6\beta}{Re_D}\right)^2 + (0.0188 + 0.0063A)\beta^{3.5}\left(\frac{10^6}{Re_D}\right)^{0.3} + (0{,}043 + 0{,}080e^{-10L_1} - 0{,}123e^{-7L_1})(1 - 0{,}11A)\frac{\beta^4}{1-\beta^4} - 0.031(M_2 - 0.8M_2^{1.1})\beta^{1.3} \tag{2}$$

$$\epsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8)\left(1 - \left(\frac{P2}{P1}\right)^{1/\kappa}\right) \tag{3}$$

$$L_1 = \frac{l_1}{D},\quad L_2 = \frac{l_2}{D},\ A = \left(\frac{19000\beta}{Re_D}\right)^{0.8},\ M_2 = \frac{2L_2}{1-\beta}, Re_D = \frac{4Q_m}{\pi\mu D}$$

Where C is the discharge coefficient, ϵ is the expansion coefficient, β is the relation between the orifice and pipe diameter, d is the orifice diameter, D is the pipe diameter, ρ is the flow density, ΔP is the difference the pressure before and after the obstruction, L1 and L2 are the distances from the pressure tapes and the plate, *k* is the isentropic exponent of the flow and ReD is the Reynolds number.

Root Mean Square Error

It is an indicator that measures the average difference between two data sets. It is usually applied for the comparison of a set of known or certain data and a set of measured data. In turn, it us used as a standard statistical metric to measure model performance in many fields of studv [11]. The RMSE is defined mathematically as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}|x_i - y_i|^2}{N}} \tag{4}$$

III. RESULTS

The design process that was carried out during this project was approached in two phases, the first one that provided a path to generate inventive solutions ideas and a second one to make possible a structured analytical process. Thus, through a conjunction of design methodologies TRIZ, Design Thinking, the structuring proposed by the axiomatic design and the use of AHP as a tool for decision making, led to a correct procedure and execution in the implementation.

The understanding of the problem was carried out by means of the TRIZ inventive method, with which the most relevant aspects involved in the problem were broken down, providing a spatio-temporal vision of the solution to be developed, facilitating the visualization of ideal attributes that should be implemented in the solution system and highlighting which aspects should be improved. Subsequently, the axiomatic design was articulated to the results obtained from the TRIZ method, clarifying the system requirements, allowing the determination of the design ranges, and opening the way to a wide range of alternatives with which the solution could be implemented. It is here where the AHP decision making tool provides an evaluation process that considers the characteristics of the entire set of alternatives, facilitating the choice of alternatives that optimally meet the requirements. Now, contemplating the solution alternatives, the procedure to the implementation, which was supported by the Design Thinking methodology, allowed to make an iterative prototyping process, considering the users feedback in each of them, approaching a better solution. During this process, two prototypes were implemented and also a theoretical approach that sought to improve the estimation of the respiratory flow of the orifice plate sensors.

The implementation process required the construction of an experimental set-up presented in fig. 1 it captures the inspired and expired air through a sealed oxygen mask and conducts it to the orifice plate sensor which was also equipped with a differential pressure transducer that provides a proportional voltage signal.

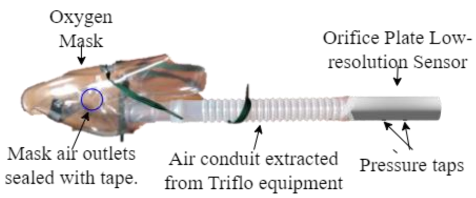

Fig. 1 First experimental set-up

Prototype 1: NI LabVIEW and SparkFun Pro Micro

In this prototype a voltage acquisition system was developed using a SparkFun Pro Micro microcontroller to read the transduced voltage and send its value to a computer through a serial port, which in turn was responsible for processing the signal in a LabVIEW platform, with which a graphical representation of the physiological variables involved in the respiratory process, such as flow, volume, and respiratory rate, was developed. The general operation of this prototype is represented by the flowchart in fig. 2, while the processing executed on the LabVIEW platform is presented in fig. 3.

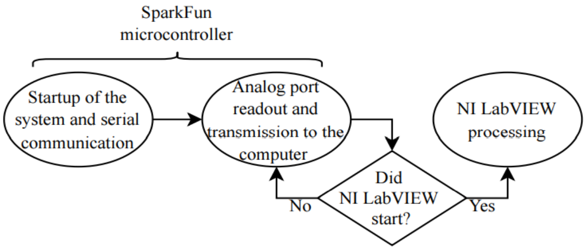

Fig. 2 Simple flowchart of the prototype operation

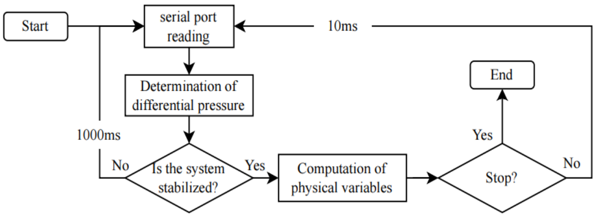

Fig. 3 Flowchart for NI LabVIEW processing prototype

Prototype 2: SparkFun Pro Micro and Bluetooth Transmission

The second prototype developed implements an integration of a wireless communication via Bluetooth and additionally makes possible a conditioning stage of the voltage signal from the differential pressure transducer, the general operation of the prototype is represented in fig. 4. Similarly, to the prototype 1, the volage signal was processed but in this case the execution was implemented directly in the microcontroller, leaving aside the LabVIEW platform. Besides, the estimation of the respiratory flow value was given through the evaluation of a polynomial equation extracted from an interpolation of an experimental procedure in which a controlled flow was injected, and the generated voltage value of its response was directly measured.

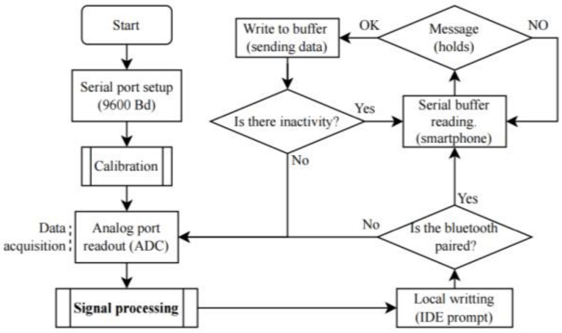

Fig. 4 General flowchart for second prototype

Orifice Plate Sensor for Respiratory Flow Measurement

Considering now how was reached the obtention of a better estimation of the flow behavior through an Orifice Plate sensor, it was needed to reefer to a common design standard such as ISO 5167, which presents a mathematical model that is intended for industrial implementation of Orifice Plate Sensors, guarantying only right estimations for large flow values in pipes with a diameter greater than 50mm. This fact led this project to the introduction of an adaptation of the model by reformulating the discharge (eq. 1) and expansion coefficients (eq. 2). These two coefficients were experimentally developed by the University of Texas in collaboration with the Celaya Institute [12].

$$C = a_1 + a_2\beta^{3.75} + a_3\beta^4 + a_4\left(\frac{\Delta P}{P1}\right)^{1.25} + a_5\left(\frac{\Delta P}{P1}\right)^{2.25} \quad (5)$$

$$\epsilon = b_0 + b_1\frac{\Delta P}{P1} + b_2\left(\frac{\Delta P}{P1}\right)^2 + b_3\left(\frac{\Delta P}{P1}\right)^3 \quad (6)$$

Table 1. Values of the constants of the new formulations

a1 = 0.59865	b0 = 1
a2 = 0.81891	b1 = -0.5046
a3 = -0.86143	b2 = -0.1615
a4 = 0.25169	b3 = -0.0582
a5 = -2.2216	

Additionally, the model in the ISO 5167 was modified by adding a multiplicative constant that improved the amplitude error in the estimation. It is then how the model that estimates the value of the respiratory flow considering medical applications, finally results in:

$$Q_v = \frac{KC\epsilon}{\sqrt{1-\beta^4}}\frac{\pi d^2}{4}\sqrt{\frac{2\Delta P}{\rho}} \quad (7)$$

In turn, the methodology developed for the design of the dimensions of an adequate orifice plate sensor for this medical application, considers the maximum design ranges, results from applying a design process analogous to the one developed for this standard, now evaluating the new formulations of the coefficients. Fig. 5 shows the orifice plate sensor finally designed.

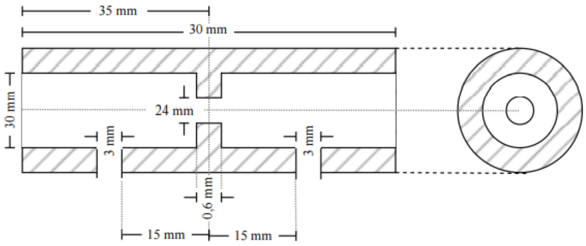

Fig. 5 Designed Orifice Plate Sensor dimensions

Furthermore, the estimation of the other two fundamental physiological variables in lung re-expansion physiotherapies: Volume and Respiratory Rate, were the result of digital processing of the respiratory flow signal obtained.

The respiratory volume was estimated from the resolution of the relationship between flow and volume, by discretizing the problem using the trapezoid rule [13], the flow diagram presented in fig. 6, follows the behavior of the implemented solution.

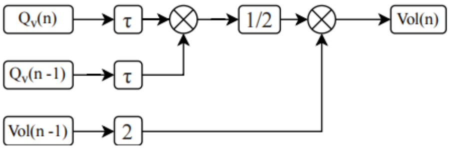

Fig. 6 Flowchart of the respiratory volume estimation.

The respiratory rate, in turn, was implemented by means of an accumulator of falling edges of the respiratory flow during a period of 20s, to be subsequently scaled to the required standard measurement, breaths per minute, as follow:

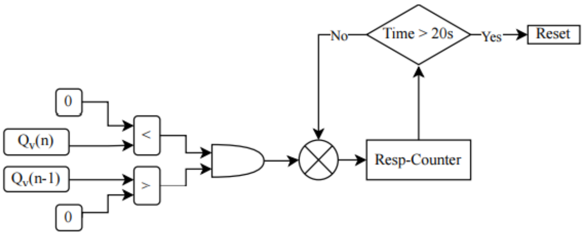

Fig. 7 Flowchart respiratory rate estimation.

Moreover, the evaluation of the estimation achieved by the adapted model was checked by point-to-point comparison of flow values in an orifice plate sensor extracted from an experimental setup that related the flow and differential pressure, the result is presented in fig.8.

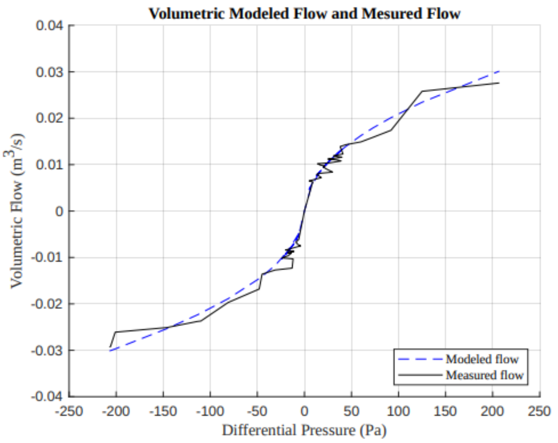

Fig. 8 Respiratory flow estimated by the model and the experimental flow measured

The RMSE factor between the set of values obtained experimentally and those obtained from the model estimation yielded a value of 0.0017 m^3/s, which indicates a good approximation for this project.

Finally, the electronic device implemented is presented in fig. 9, which compiles the circuit elements of the voltage signal conditioning, the module for Bluetooth communication and a suitable assembly for the microcontroller.

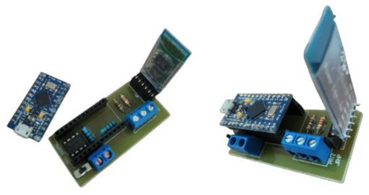

Fig. 9 Acquisition electronic device

IV. DISCUSSION AND CONCLUSIONS

The development of this project not only led to the implementation of an electronic system capable to carry out the monitorization of physiological variables of flow, volume and respiratory rate in a lung re-expansion physiotherapy, but also made an adaptation of a suitable model for flow estimation in an orifice plate sensor, oriented to a medical application, considering small air flows in pipes with diameters according to the application, where a satisfactory result of an RMSE error of 0.0017 m^3/s between the estimate and the actual flow values in the sensor was obtained.

Besides, the conjunction of TRIZ and Design Thinking design methodologies and the articulation of Axiomatic Design and AHP decision making methodology, provided the necessary tools and strategies to address the design problem in an organized and structured way, proving that these design procedures can help to achieve an adequate implementation process for engineering problems, guiding designers to obtain good results.

In turn, the adaptation of the model for the estimation of respiratory flow for an orifice plate sensor and the electronic device designed open the possibilities to the applications that can be achieved, beyond the support of lung re-expansion physiotherapies, but it could also implement applications as a multipurpose spirometry equipment, among others.

Finally, it is important to highlight the teamwork as part of the research project which provided the necessary resources and additionally, allowed the improvement of communication skills in a multidisciplinary environment, which also broadened the knowledge in other areas and demonstrated the versatility of the applications that can be achieved in engineering.

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