An Intelligent Control System Architecture for the Control of Patient-Ventilator Synchrony

Dalton S. Nelson
Department of Electrical and Computer Engineering
University of Alabama at Birmingham
Birmingham, AL 35294-4461 USA

Thomas C. Jannett
Department of Electrical and Computer Engineering
University of Alabama at Birmingham
Birmingham, AL 35294-4461 USA

James H. Strickland, Jr.
Pulmonary and Critical Care Medicine
Saint Vincent's Hospital
Birmingham, AL 35202 USA

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Abstract - **This paper describes an intelligent control system architecture for the control of patient-ventilator synchrony. The long-term objective of the research is to develop an innovative intelligent system for controlling the process of mechanical ventilatory support for patients undergoing therapy in a hospital intensive care unit (ICU). The initial work focuses on the requirements for a medical-advisory/decision-support system. The hierarchical structure of the system is organized around three main processing levels, a Sensing/Perception Level, a Planning/Coordination Level, and a Supervision/Control Level. Using measured data from the patient, heuristics gleaned from experienced clinicians, and intelligent planning and control principles, the overall system is expected to provide significant improvements in the quality of care given to patients needing such therapy.**

I. INTRODUCTION

Mechanical ventilation is the process whereby a machine is used to provide artificial support to the respiratory system of critically ill patients experiencing respiratory failure [1]. There are many medical reasons why a patient may need such therapy, including respiratory diseases such as emphysema and bronchitis, and paralysis of the muscles involved in breathing resulting from anesthesia or head injury, where the nerves controlling breathing may be impaired. The patient is usually placed in the Intensive Care Unit (ICU) of a hospital or clinic, where they are coupled to a ventilator through an endotracheal tube connected through the mouth to the trachea (windpipe), thus facilitating the flow of gases (air, or pure oxygen) to the lungs. The primary therapeutic goal of ventilator therapy is to reduce the work that the patient performs in breathing, while also ensuring that an adequate amount of oxygen is taken in during inspiration, and proper levels of carbon dioxide are eliminated during expiration. The ventilator may be set to provide full support in cases where the patient does not initiate any breaths (i.e. there is no spontaneous breathing on the part of the patient), or it may be set to provide partial support, in which case some or all the breaths delivered by the machine are triggered by the patient's inspiratory efforts. Partial support allows the patient to receive a breath when needed and reduces the work that the patient performs in breathing.

The ventilator delivers a number of breaths per minute (respiratory rate, RR). For each breath gas is delivered to the patient during an inspiratory phase. The patient passively exhales during an expiratory phase. The inspiratory-expiratory time ratio (I:E ratio) is the ratio of the duration of the inspiratory phase to that of the expiratory phase. The tidal volume is the volume of gas delivered to a patient during the inspiratory phase. In a typical partial support situation, the tidal volume is initially set based on patient characteristics, and a constant inspiratory flow is set to a value which keeps the resulting peak airway pressure from exceeding safe limits. The resulting inspiratory time would be the tidal volume divided by the inspiratory flow. After the inspiratory phase, the patient exhales. In partial support, the next inspiratory phase would typically be triggered by a small negative excursion of the airway pressure resulting from the effort of the patient to inhale.

The medical condition of critically ill patients can change quite rapidly and suddenly, requiring that clinical personnel with a high degree of expertise and experience provide close monitoring of the patient, and be ready to take corrective action as needed to ensure adequate ventilator support, patient safety, and optimal therapy. Spontaneous breathing efforts made by the patient may not coincide with the breaths delivered by the ventilator. "Patient-ventilator dysynchrony" refers to situations where the settings on the ventilator do not correctly match the respiratory needs of the patient. If the clinical staff is not vigilant enough to detect such events, and take the appropriate corrective action, the patient can suffer considerably. In practice, it is both difficult and expensive for hospitals to provide personnel with the necessary experience and expertise at the patient's bedside, resulting in less than ideal conditions for the patient.

Events associated with patient-ventilator dysynchrony can often be detected by examination of the respiratory waveforms that are displayed on modern ventilators. Fig. 1 shows computer simulations of the typical appearance of these waveforms during normal respiration. Dysynchronous events in the ventilation process are characterized by the presence of various types of alterations in the normal waveshapes. Corrective action entails incremental adjustment of the ventilator to alleviate the problem.

There are numerous possibilities for what combinations of mismatches between ventilator settings and patient needs might trigger a dysynchronous event. For the purpose of this system development focus will be placed on four types of events associated with use of the ventilator providing partial support. These are Tidal Volume Too High, Tidal Volume Too Low, Inspiratory Flow Too High and Inspiratory Flow Too Low.

If, for example, a patient who is able to initiate some breaths is put on a ventilator for support, but with the tidal volume setting on the ventilator too low, the patient might try to breathe in for a longer period than the machine delivers gas. As a result, when the machine stops delivering gas to allow for exhalation the patient will be still trying to inhale and a "fight" between the patient and the machine will ensue. This "fighting the ventilator" condition is a dysynchronous event, and appears as a series of transient oscillations in the decay portion of the pressure-time and volume-time curves, and as stair-step changes in the decay portion of the flow-time curve. The other dysynchronous events are manifested in a variety of ways.

Control Requirements

Based on the perceived condition [2-3] of the patient, the clinician relies heavily on the use of heuristics (clinical "rules of thumb") to know when, and in what way, to adjust the ventilator. The patient's vital signs, physical appearance, and information from the ventilator waveforms are all useful in the clinician's determination of patient-state. The relationship between the patient's perceived medical state and the desirable ventilator settings is, however, nonlinear. The ventilation process to be controlled is also subject to many uncertainties, a high degree of complexity, coupled with many parameter and state variations over time. Some aspects of the process are not easily described by mathematical models.

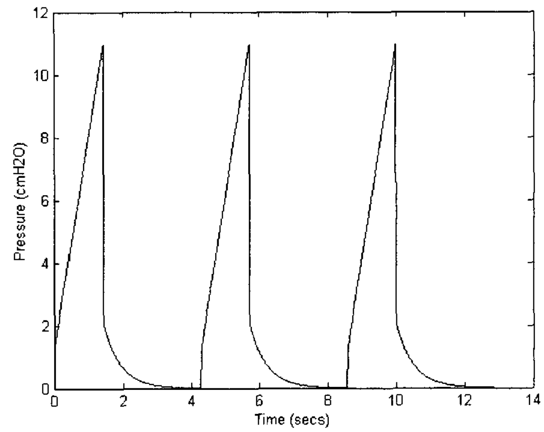

Fig. 1A: Pressure

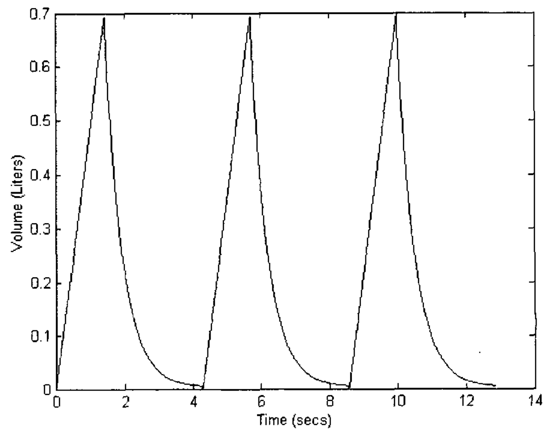

Fig. 1B: Volume

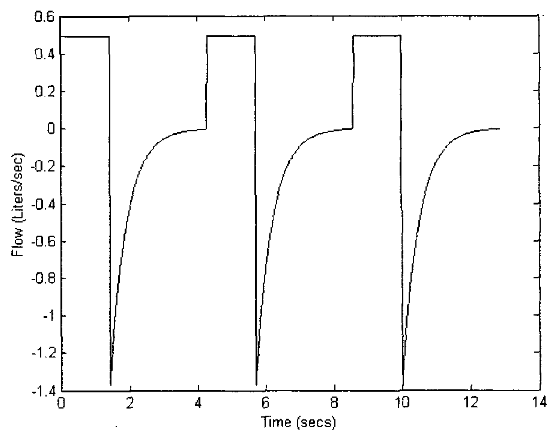

Fig. 1C: Flow

Fig. 1: Simulated ventilator waveforms (A – pressure, B – volume, and C – flow) for three breaths with good patient-ventilator synchrony. Ventilator parameters are: respiratory rate (RR), 14 breaths per minute (BPM), inspiratory-expiratory time ratio (I:E ratio), 0.5, and tidal volume, 0.7 Liters.

These factors make it very difficult, if not impossible, to properly control many aspects of the process using classical and modern control techniques. Intelligent control offers great promise for solving various aspects of these difficult control problems. Reports of intelligent control applications in mechanical ventilation are sparse, but almost all such schemes use some kind of rule base to facilitate the inclusion of the expert knowledge and heuristics of the clinician in control algorithms. Fuzzy logic, neural networks, genetic algorithms, and signal processing techniques, used in various combinations, may be employed to mimic the complex decision-making processes of humans [4-11].

Patient-ventilator dysynchrony resulting from improper ventilator settings produces airway pressure events that will be detected and used as feedback signals in the new control system. In situations where ventilator adjustments are needed, an algorithm will automatically suggest needed adjustments in the ventilator settings for respiratory rate, inspiratory flow, inspiratory:expiratory (I:E) time ratio, and tidal volume to achieve optimal patient-ventilator synchrony and, hence, minimal patient work of breathing. Since the detection of dysynchronous events does not provide much information about what magnitude of ventilator adjustment is needed, the control algorithms must be designed to make gradual adjustments to match the needs of the patient. This approach could allow changes in the patient's physiological status to be determined by tracking parameter changes in a model of the patient's respiratory system mechanics, such that necessary ventilator adjustments will be anticipated and made early, instead of waiting until the patient develops serious dysynchrony or complications from inadequate ventilation. Ventilator adjustments will be constrained to accommodate the range of inspiratory flows that can be delivered by the ventilator, maximum airway pressure, maximum tidal volume, and a minimum I:E time ratio.

This paper presents the basic architecture of an intelligent control system intended for use in the control of patient-ventilator synchrony. The initial development is focused on a medical-advisory/decision-support system. It is possible that this system may later be extended to carry out closed-loop control of some aspects of the ventilation process. The system architecture is designed to allow testing of various control algorithms as they are developed, and to fit within the structure of an intelligent control hierarchy that allows interactive communication with the expert clinician. Fig. 2 shows a simplified block diagram of the overall control scheme.

II. INTELLIGENT CONTROL ARCHITECTURE

The control architecture chosen for this development serves mainly as a framework for the detailed design of various subsystems, and in no way dictates the implementation technologies to be used. It has been found that this level of abstraction (a macroscopic view) is very useful in identifying

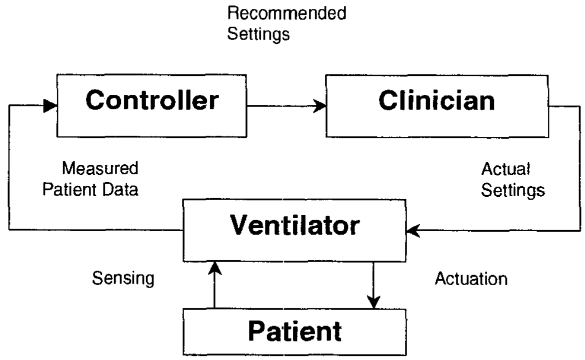

Fig. 2: Simplified overall system diagram for intelligent control of the ventilation process using a medical-advisory/decision support scheme.

the various functions to be performed and their interrelationships. This approach has allowed development of the lower level processing details to advance, and some details of this part of the system will be outlined later in this paper.

The overall architecture of the system is based on a three level hierarchy. It has been shown in [12-14] that a hierarchical structure readily lends itself to partitioning of processing responsibilities, such that events requiring fast response can be catered to, while also allowing for more long term planning and forecasting activities to be accommodated. The design allows future subsystem developments to be easily incorporated into the larger system.

Fig. 3 shows the overall structure of the control system and its three levels. The Sensing/Perception level is responsible for receiving signals from the ventilation process and "making sense" of them. The Planning/Coordination level is responsible for formulating plans of action to control the ventilation process as well as coordinating the processing of

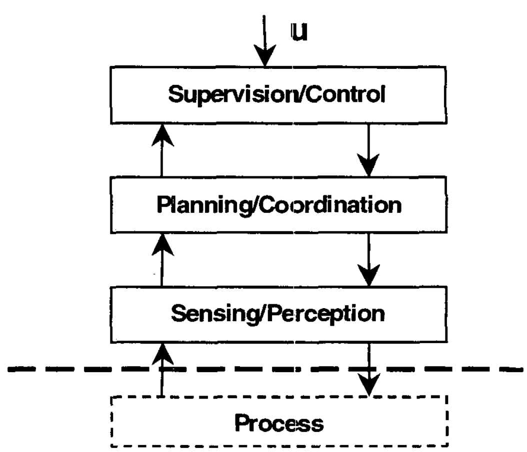

Fig. 3: Hierarchical structure of the control system, showing the three main processing levels.

higher-level control directives relative to perceived process states that might require immediate action, necessitating suspension or modification of higher level directives. The Supervision/Control level provides expert reasoning, high-level directives, process optimization, and an operator interface that allows therapeutic goals to be entered by the clinician.

Bi-directional communication lines shown between the three levels indicate data sharing. At the lowest level the data take the form of physiological signals from the patient. The Sensing/Perception level essentially transforms the process signals into a perceived situation recognition.

At the Planning/Coordination level a further transformation takes place producing a specific plan of action to be taken in response to the recognized situation. In the context of ventilation actions represent the settings to be used on the ventilator, or the generation of alarms. The plans are passed on to the Supervision/Control level for evaluation relative to the therapeutic goals set by the clinician, as well as with respect to trend information gathered over the course of the therapy process. The coordination aspect of this level manages the sequencing of control actions taken. If a recognized situation requires immediate action (an autonomous response) the plan may have to be executed directly (through the coordinator), bypassing the normal supervision/control level evaluation process, which may introduce too long a processing delay. The Supervision/Control block evaluates plans generated by the Planning/Coordination level, considering clinician-set goals, process trends, and optimization criteria.

The representational form of the process data changes as the system hierarchy is traversed from bottom to top. At the lowest level data items are in the form of precise measured values. At the mid-level data values from the lower level have become associated with a process state that is more linguistic and imprecise, or fuzzy, in its representation, e.g. "too high", or "too low". The fuzzy references are passed on to the highest level where the clinician can interpret such characterizations and upon which a (fuzzy) controller can make decisions as to control settings.

Fig. 4 shows further details of the Sensing/Perception level of the system, with an emphasis on the flow of input data and their processing. After the various signals are sensed and appropriately conditioned, they are passed to the perception level. Perception involves analyzing sensed signals in order to determine if they represent normal or dysynchronous conditions. Various techniques are under consideration for carrying out the perceptive tasks, including pattern recognition, neural networks, fuzzy logic, genetic algorithms, and signal processing. No single method may be adequate to fully and reliably identify a given type of dysynchronous event, and so several of these methods may have to be used. An Arbitrator section will judge the findings of the perception sections and make a decision on the most probable result.

III. SUMMARY

Control of patient-ventilator synchrony is complicated by the presence of nonlinearities, uncertainties, the need to balance conflicting requirements, and the lack of direct measurements of the variables to be controlled. Intelligent control methods offer considerable promise for controlling such processes, mainly by their ability to mimic the complex decision-making processes of experts in the problem domain.

This paper has outlined the basic features of an intelligent control architecture that is being used to develop a controller for patient-ventilator synchrony. Processing requirements at various levels of the hierarchical system structure have been presented. The system is initially intended to function in a medical-advisory/decision-support role to aid clinical staff involved with ventilator therapy of ICU patients.

It is currently very costly for hospitals to provide adequate numbers of clinical staff with the necessary expertise and experience to detect and correct dysynchronous events during ventilation, thus ensuring that patients are given optimal therapy. Successful implementation of the intelligent control system described promises to greatly improve the level and quality of care that can be given to ICU ventilator patients.

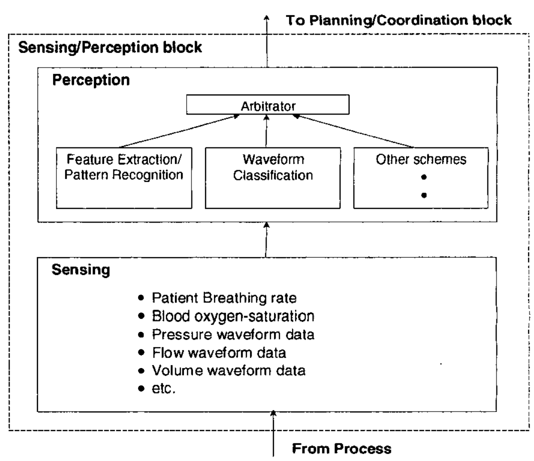

Fig. 4: Detailed view of the Sensing/Perception block.

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