Supervisory Mechanism for Oscillatory Suppression in Automatic Ventilation Therapy based on the ARDSNet Protocol

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Introduction

In order to fulfill the oxygenation goal during an automatic ventilation therapy using ARDSNet protocol, a clinical guideline based on the dual adjustment of ventilation variables, i.e. positive end-expiratory pressure (PEEP) and a fraction of inspired oxygen (FiO_2), is applied based on the feedback of peripheral saturation of oxygen (SpO_2). In only a few cases, an unexpected oscillating behavior can be observed due to a tight control of protocol-based controller in a medical expert system [1] and a variational delay of the overall closed-loop system. Since this oscillatory behavior can be occurred with a wide and changable oscillation period ranging from a minute to half an hour, it is therefore a challenge to detect possible oscillation in the control loop and trigger further supervisory mechanism for oscillation suppression.

Methods and Materials

For integrating smart ventilation mechanism based on the ARDSNet protocol, oscillation detection and reasonable control action should be implemented in order to avoid possible detrimental effect on a patient under automatic ventilation therapy.

System Architecture

A closed-loop control system of oxygenation with the corresponding parameters can be configured based on the oscillation detection and supervisory mechanism with the underlying protocol-based controller, as shown in Fig. 1.

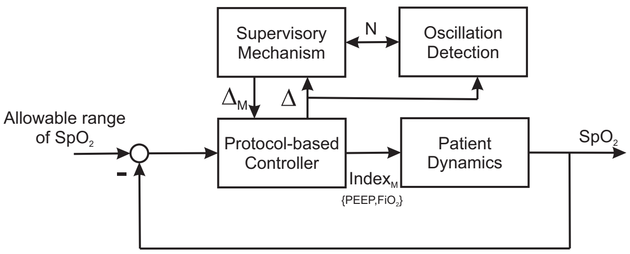

Fig. 1: Configuration of closed-loop oxygenation therapy with supervisory control based on ARDSNet protocol.

With this extended supervisory mechanism, not only oxygenation goal based on the PEEP/FiO_2 table can be satisfied, but also a higher level of smart ventilation should be delivered to a patient with acute lung injury for oscillatory suppression in the oxygenation.

System Formation and Notation

Based on the automatic ventilation therapy using ARDSNet protocol, the dynamical states can be considered in a discrete-time domain. The analysis of control algorithm is subsequently performed on the vector Index $\in \{1,2,...,17\}$, which is defined and restricted in a positive finite set corresponding to the 17 different combinations of ventilation variables (PEEP and FiO_2). The vector $\Delta \in \{-1,0,1\}$ represents a series of possible normalized control action with a reference to a previous index in the original ARDSNet protocol. The sampling time for this implementation is 30 s [1]. The protocol-based controller produces a fictitious variable Index(i) at the sampling i and eq. (1) conserves the constraint relationship of saturation behavior ($Index_{min}(i)$=1 and $Index_{max}(i)$=17) with memory effect of previous state.

$$\mathrm{Index(i)} = \mathrm{Index(i-1)} + \Delta(\mathrm{i}) \tag{1}$$

The cumulative sum of Δ series is denoted by a parameter sum_Δ, which can be computed by

$$\mathrm{sum}_\Delta(\mathrm{i}) = \mathrm{sum}_\Delta(\mathrm{i}-1) + \Delta(\mathrm{i}). \tag{2}$$

The zero-crossing points can be analyzed based on the curve of $sum_\Delta \in \mathbf{I}$ and a parameter $N \in \mathbf{I}^+$ represents the number of zero crossing points. The proposed supervisory mechanism for oscillatory suppression will generate and modify the primary vector Δ to be the modified vector Δ_M after detecting oscillation, yielding the new setting of ventilation variables in the vector $Index_M$, shown in Fig. 1.

Oscillation Detection

In order to sense the fundamental cycle of oscillation, zero-crossing is proposed for the signal sum_Δ. With the initial setting N(0) = 0, the following condition can be used to detect the zero-crossing point of $sum_\Delta(i)$ for this problem.

$$\text{Zero crossing is at i.} \rightleftharpoons \{\mathrm{sum}_\Delta(\mathrm{i}-1) \neq 0\} \wedge \{\mathrm{sum}_\Delta(\mathrm{i}) = 0\}$$

The number of zero-crossing points is actively counted in every sampling time and the formula is provided in eq. (3).

$$N(i) = \begin{cases} N(i-1)+1, \text{ for } i \text{ at a zero}-\text{crossing point} \\ N(i-1), \text{ for } i \text{ elsewhere} \end{cases} \quad (3)$$

A change of N(i) indicates a zero-crossing point at the i sample.

Supervisory Mechanism

A supervisory mechanism is established to relax a strict control of oxygenation. Its function is to suppress the possible oscillation in the control loop and stabilize the states to the predetermined bound region. The primary clinical-based decision $\Delta(i)$ is modified to $\Delta_M(i)$ based on N(i) parameter using the following algorithms.

$$\{N(i)=3\} \rightarrow \{i_0 = i\} \wedge \{N(i_0)=0\} \quad (4)$$

$$\Delta_M(i) = \begin{cases} 0, \text{ for } i \leq i_0 + i_h \\ \Delta(i), \text{ for } i \text{ elsewhere}, \end{cases} \quad (5)$$

where i_h (= 40 for simulation purpose) denotes the span of holding points and i_0 represents the sampling point where oscillation is detected.

Results

A simulation result is shown in Fig. 2, based on an initial arbitrary Index within the restricted range and a uniform random variable Δ. Not only the oscillation detection can be implemented by zero-crossing approach of sum_Δ, but also the oscillatory suppression can be fulfilled by introducing an adaptive time for oxygenation goal from 1 sample to i_h sample. Ater an oscillation detection, Δ_M becomes and remains zero for i_h sample.

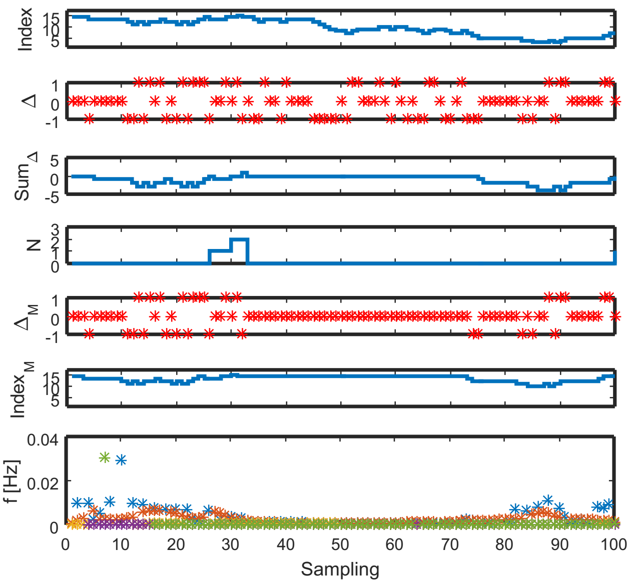

Fig. 2: Simulation of the supervisory control for oscillatory suppresion in the automatic ARDSNet protocol.

For manipulating a wide class of nonstationary and nonlinear signal, Hilbert spectrum [2] is applied for the frequency-time analysis of the normalized controlled signal Δ_M with the sampling time of 30 s. The underlying instantaneous frequency is in a range of 0 Hz to 0.04 Hz, demonstating the oscillation detection in frequency domain based on the intrinsic mode function.

Discussion

A supervisory algorithm is designed for intelligent control action in the closed-loop ventilation system based on the ARDSNet protocol. The potential problem of oscillation in the controlled variables is handled in a discrete-time domain. An intermediate variable N is proposed for oscillation detection using zero-crossing approach and the controlled variables (PEEP and FiO_2) [3] are overrided for oscillatory suppression. Different initial settings corresponding to a variation of patient's severity based on the Berlin Definition, namely mild, moderate and severe cases, are covered in the simulations. The new supervisory control system is also capable of handling all eight cases of oscillation with different signs of sum_Δ between the zero-crossing points, i.e. '+++', '+-+' or '-++' and a variation of unexpected oscillatory frequency can be detected. Furthermore, a number of simulations with uniform random distribution confirms the feasibility of this algorithm in the real clinical scenarios. Nevertheless, patient-in-the-loop should be implemented and tested.

With Hilbert-Huang transform [2], a local nature of instantatneous frequency is extracted the intra-wave frequency modulation and gives us an insight of oscillatory frequency. It should be noted that the empirical mode decomposition is an *a posterior*-defined basis.

Conclusion

We introduce a concept of higher and complex class of automatic ventilation therapy based on the ARDSNet protocol to suppress potential oscillation in the oxygenation goal. Based on the proposed algorithm, a number of simulation results verify its reliability and feasibility in practice.

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