A rapid control prototyping system for the automated control of mechanical ventilation

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Abstract: The automated control of mechanical ventilation requires the merging of the disciplines of control engineering and clinical knowledge from intensive care medicine. To design and accurately implement the clinical expertise it is of paramount importance to keep clinicians involved throughout the programming phases to accommodate dynamic changes in mechanical ventilation strategies. A rapid control prototyping system is presented which allows the quick implementation and testing of new control laws. Furthermore, by choosing a graphical programming language, the clinicians remain on-board. An automated compliance-based PEEP titration and rule-based FiO_2 control are shown as exemplary results for oxygenation control during protective ventilation using MATLAB Stateflow®.

I. Introduction

Supportive care with mechanical ventilation remains the standard treatment method for patients suffering from the Acute Respiratory Distress Syndrome (ARDS). Correctly choosing ventilator settings, however, remains a challenging and time consuming task, which requires the full attention of the clinician. Automated control of mechanical ventilation closes the loop with a controller instead.

I.I. Physiological Closed-Loop Control

The idea to move from clinician-in-the-loop systems to physiological closed-loop control (PCLC) of mechanical ventilation has been around for almost 50 years, with varying degrees of success [1]. The adoption of PCLC is complicated by the fact that the goals of mechanical ventilation continue to change, with the current focus being on protective ventilation strategies, in addition to the previous goals concerning oxygenation and carbon dioxide removal [2]. Furthermore, the diversity of patients and illnesses necessitates a personalized ventilation strategy, which requires clinical expertise.

For accurate and useful automated control of mechanical ventilation, the merging of control engineering and clinical expertise is necessary. However, during implementation of algorithms, the clinical expertise often gets lost in translation between engineers and doctors. The resulting algorithm tends to remain a black box for clinicians, which they then seldom trust, and hence do not use [3].

The goal of the rapid control prototyping platform is to firstly, quickly implement and test the control strategies, secondly apply changes to the algorithms on the fly and thirdly, make the programming of algorithms more insightful to the clinical partners.

II. Material and methods

The rapid control prototyping system is configured as shown in Fig. 1.

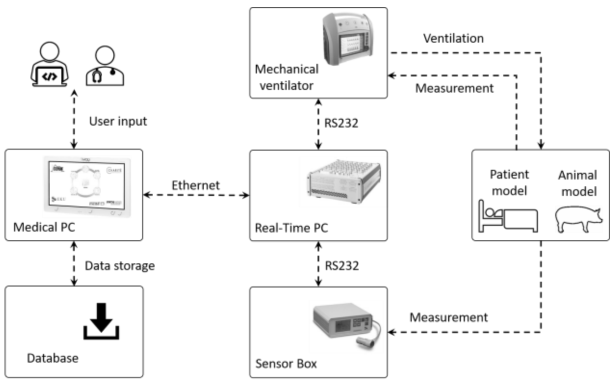

Figure 1: Rapid Control Prototyping system for the testing of automated mechanical ventilation.

At the heart of the system is a real time PC (MicroLabBox, dSPACE GmbH, Paderborn, Germany), which communicates with a medical panel PC (THA.leia³, MCD Medical Computers Deutschland GmbH, Mönchengladbach, Germany) running MATLAB 2017b (The MathWorks Inc., Natick, USA) and dSPACE Control Desk ver. 7.1. A modified mechanical ventilator (EVE,

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Fritz Stephan GmbH, Gackenbach, Germany) can receive remote commands from the real time PC and sends all ventilation data via the RS232 protocol. Additional sensors for airway or esophageal pressure can be connected to a custom sensor box (EKU Elektronik GmbH, Leiningen, Germany), which also communicates with the real-time PC via the RS232 protocol.

The patient model consists of a physical lung simulator (LS800, Drägerwerk AG, Lübeck, Germany) and physiological computer models. The physical lung simulator allows for varying compliance and resistance values and can be used to replicate various diseased lung states. In an ongoing animal study, the patient model is replaced by a porcine model with induced ARDS.

II.I. Expert System

The programming of the control algorithms is performed in MATLAB Simulink® and MATLAB Stateflow®. Stateflow® is a graphical programming language tool to model reactive systems using state machines and flowcharts. Hence clinical flowcharts can be quickly programmed but remain understandable to persons without a programming background.

The development of new physiological closed-loop control algorithms is part of ongoing research, but some exemplary results are shown here.

Firstly, the positive end-expiratory pressure (PEEP) is a particularly difficult ventilator setting to correctly set. One method to set the PEEP is to use a decreasing PEEP titration maneuver [4]. Here the PEEP setting is stepwise reduced after a certain time interval and the respiratory compliance is observed on every step. The PEEP setting with the highest compliance is then referred to as the "best PEEP". This lends itself well to automation.

Furthermore, titration of the fraction of inspired oxygen (FiO_2) is used to keep the oxygen saturation (SpO_2) within a target range. As an example a rule-based FiO_2 controller, based on clinical knowledge, is used to increase or decrease the FiO_2 to keep the oxygen saturation within the target of 92 ± 1 %. The rules are set out in Table 1.

Table 1: Rules for the FiO_2 controller

SpO_2 [%]	Action
> 95	Decrease FiO_2 by 5% every 80 sec
$95 \geq SpO_2 > 93$	Decrease FiO_2 by 2% every 80 sec
$93 \geq SpO_2 \geq 91$	Idle
$91 > SpO_2 \geq 89$	Increase FiO_2 by 2% every 40 sec
< 89	Increase FiO_2 by 5 % every 20 sec
< 85	Set FiO_2 = 100 %

III. Results and discussion

An initial test of the system using the above expert system was performed in a porcine model. ARDS is induced through multiple lung lavages and high tidal volume ventilation.

After ARDS has been confirmed, the expert system is started and the result is shown in Fig. 2. The system begins with an automated PEEP titration (1) and selects a "best PEEP" according to compliance (2). Initially the FiO_2 is slowly titrated down to bring the oxygen saturation into the target region (3), where it is held for the duration of the test. At the markers (4-6) the FiO2 is automatically adapted to compensate for disturbances from changes in medication and hemodynamics.

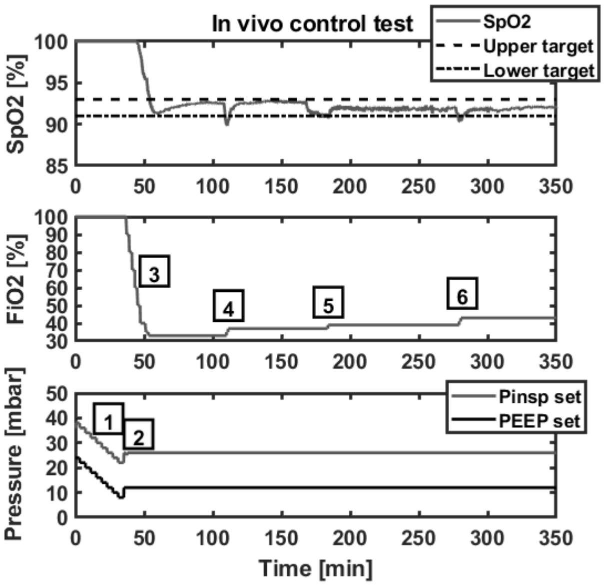

Figure 2: Results of the expert system in a first in vivo test. An automated PEEP titration and FiO2 control are performed by the system.

IV. Conclusions

A rapid control prototyping system for the automation of mechanical ventilation has been presented. The clinical expertise is programmed in a transparent way, and an automated PEEP titration and FiO_2 controller were successfully tested in vivo. In future, this system will be used to develop more advanced physiological closed-loop control algorithms, and allow for the fast testing and validation in patient models and animals studies.

Author's statement

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