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Control of the fraction of inspiratory oxygen of a decentralized breathing gas source

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Abstract: This contribution proposes a method of controlling the fraction of inspiratory oxygen (FiO₂) by actuating the outflow of a commercial concentrator through the attachment of a stepper motor. The idea is to include available devices as such that breathing gas with an increased fraction of inspiratory oxygen (FiO2) can be provided in case a vast amount of patients need to be ventilated without sufficient infrastructure regarding high pressure supply lines or the distribution of oxygen bottles. The designed system was identified regarding its static and dynamic behaviour which was then used to tune a PI controller. The dosage was tested with the concentrator's outflow only and on the other hand in combination with a simple ventilation mode (VCV) in which a parallel blower supplied surrounding air into the dosage chamber as well. The results showed that the working principle fulfills its purpose, however further optimization is needed, especially for the systems response speed and precision.

I. Introduction

The Covid-19 pandemic came with a significant shortage of mechanical ventilators for the intensive care unit (ICU) [1]. It also revealed a limited oxygen supply infrastructure in the hospitals [2] as the consumption could not be covered and supply lines were not stable for a vast amount of patients simultaneously. Even the additional usage of oxygen bottles was restricted by its distribution in some countries. Therefore, a solution would be beneficial in which the breathing gas is dosed independently of the infrastructure and as a result dedicated ventilators with a decentralized concept for oxygen production could address this problem [3]. For this purpose, a test bench was built consisting of a blower and concentrator whose outputs are mixed in a chamber [4]. In previous work the system was already validated on a test lung, however the automatic dosage of the FiO_2 was not possible yet as the concentrator's outflow was only manually adjustable. Therefore, a method of controlling the FiO_2 is presented: by regulating the concentrator's valve through an attached stepper motor.

II. Material and methods

II.I. System design

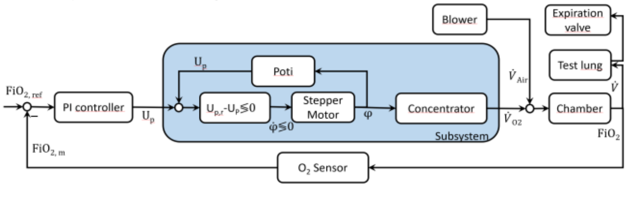

Figure 1: Concept of the designed system for oxygen control.

The system is designed following the concept shown in Fig. 1. Inside the subsystem a stepper motor is attached to the valve of a concentrator through a belt as shown in Fig. 2a. This ensures that every change of the motor's angle φ also changes the angle of the rotational knob which is opening and closing the concentrator's valve. A rotational potentiometer is frontally attached to the motor to estimate a definite measure of its position and to ensure that the range of rotation is limited for the protection of the concentrator's valve. An Arduino Uno is used to read out the potentiometer's voltage U_p and to compare it to a desired voltage $U_{p,ref}$. The motor is then turned in the corresponding direction to reduce the voltage error e_U with an estimated ratio of steps per voltage to a certain confidence interval. The potentiometer voltage U_p is aligned to the valve's position as such that 0 V corresponds to a fully closed state. That way the subsystem in Fig. 1 provides a specific flow $\dot{V}_{O_2}$ (output) for a given reference voltage $U_{p,ref}$ (input). The flow of oxygen is added by surrounding air flow $\dot{V}_{Air}$ through a blower. The fraction of oxygen is measured inside the dosage chamber and fed back to a PI controller. Here the target value $FiO_{2,ref}$ is compared to the measurement $FiO_{2,m}$ and $U_{p,ref}$ is set to achive a specific flow. The overall system is controlled using a dSPACE AutoboxII with Simulink and Controldesk. Fig. 2b shows the second part of the hardware setup including the blower, the dosage chamber and the test lung.

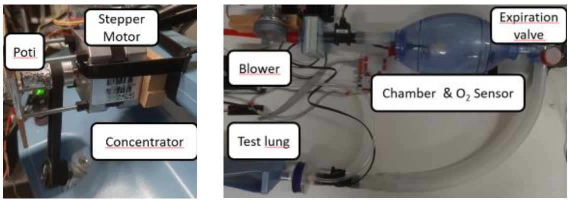

Figure 2a: Attachment of the stepper motor and potentiometer to the concentrator (left). Figure 2b: Ventilation setup (right).

II.II. System identification

The designed system was identified regarding its static and dynamic behavior. For this purpose, the motor was turned in intervals of half revolutions and the corresponding values of the potentiometer voltage U_p and outflow $\dot{V}_{O_2}$ were measured. The relationship was found to be approximately linear between 0 and 2.13 V and 0 and 5 l min^{-1}, respectively. Therefore, the output of the controller was limited to the given voltage. The dynamic behaviour between the potentiometer voltage U_p and $FiO_{2,m}$ was examined while covering the dynamics of the motor, the concentrator's valve, the oxygen accumulation in the breathing bag and the oxygen sensor (DRC D-05) all-in-one. The system response was approximated by a first order system with delay as shown in equation (1) with static gain K = 62.89, time constant τ = 50.98 s and delay T = 7.22 s. The oxygen sensor was calibrated on one point while being exposed to surrounding gas concentration.

$$G(s) = \frac{K}{1 + \tau\, s} e^{-T\, s} \tag{1}$$

II.III. Controller design

Assuming the SISO system $U_p - FiO_2$ to be linear within the working range, the method of Ziegler-Nichols was applied in order to tune a PI controller with $K_P = 0.1011$ and $K_I = 0.0042$.

III. Results and discussion

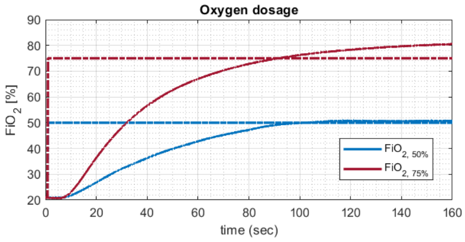

Figure 3: FiO_2 step responses for two different targets of 50 % and 75 % in the isolated dosage chamber.

The designed controller was applied with different target values of FiO_2 to the isolated breathing bag resulting in the step responses shown in Fig. 3 and the characteristic values listed in Tab. 1. In both cases the overshoot results in the steady state error as the concentration can not be lowered anymore once reached. One reason for the lack of precision is the confidence interval that has been set in order to avoid oscillations around the target voltage $U_{p,ref}$ while comparing an analog signal U_p. Secondly, the concentrator's valve can not be closed completely for long as the pressure within increases steadily which limits the range of the actuating variable $U_{p,ref}$.

Table 1: Step response characteristics

$FiO_{2,ref}$	Rise time [s]	Overshoot [%]	Steady-State Error
50 %	64.61	2.75	0.73
75 %	55.02	8.99	6.74

The identification of the step response was repeated while performing a volume controlled ventilation mode (T_V = 200 ml, RR = 12 min^{-1}) and the following parameters where found: Static gain K = 42.96, time constant τ = 16.02 s and delay T = 7.52 s resulting in $K_P = 0.0446$ and $K_I = 0.0018$. The obtained oxygen trajectory for reference levels from 30 to 60 % is shown in Fig. 4 with a maximum concentration of 59.4 %. This shows that each breath generated by the blower with non-oxygen enriched fresh gas can be compensated by an adjusted concentrator setting.

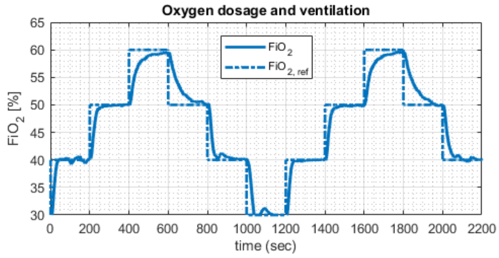

Figure 4: FiO_2 for different targets of 30 % to 60 % with additional ventilation.

For further improvement, a disturbance control could be introduced to react faster to rapid decays of oxygen levels. As the disturbance is occurring periodically also an iterative learning control approach could be used. Moreover, oxygen bottles for the demand of fast and high concentrated intervention could be combined with concentrators for the long term on lower levels. Furthermore, the setup of the oxygen sensor could be optimized as in some operation points of ventilation the measured concentration did not match the concentration at the patient. Also alternative oxygen sensor concepts with faster measuring dynamics could be evaluated to improve the reaction of the system.

IV. Conclusion

In this contribution a simple approach for controlling the FiO_2 in a decentralized breathing gas source was proposed by actuation of a concentrator's valve. The designed system was identified with respect to its static and dynamic behavior in order to enable its control in save boundaries. The established working principle proved itself to be feasible, however the achieved oxygen concentration under the condition of ventilation is too low for an application in intensive care units which means an increased flow of high-concentrated oxygen is necessary. This could be addressed by a redesign of the breathing circuit. Further development is also needed to tackle the disturbance introduced by the surrounding air to improve the response in time and precision.

AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest.

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