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# Robust Fuzzy controller design for respiratory systems

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***Abstract*—A respiratory system combines a blower-hose-patient setup with a single lung system featuring nonlinear lung compliance. This paper explores the optimal design of resilient fuzzy control for such systems by integrating a fuzzy algorithm with a sliding mode control approach. The robust fuzzy controller, as proposed, effectively handles the system's dynamics and remains stable amidst nonlinear changes. It ensures airway flow and maintains peak pressure below critical levels despite uncertainties like hose leakage and varying respiratory effort. The findings show superior performance in reaction time, overshoot, and tracking errors compared to traditional methods. The control mechanism's parameters rise time, peak value, heave, and settlement values are independently computed, revealing an over 18% improvement in rise time and a more than 44% reduction in settling time. Simulations indicate the robust fuzzy controller outperforms the PID controller, demonstrating its efficacy for respiratory system control.**

***Keywords--Fuzzy logic, Respiratory system, Robust fuzzy controller, SMC controller.***

## I. Introduction

The COVID-19 pandemic, first emerging in Wuhan, China in December 2019, has had a profound impact globally, infecting over 174 million individuals and resulting in 4 million deaths as of mid-2021[1]. Acute respiratory failure (ARF) stands out as the primary cause of mortality, with approximately 40% of critically ill COVID-19 patients developing acute respiratory distress syndrome (ARDS) [2]. These severe cases necessitate invasive ventilation and intensive care, typically provided through ICU ventilators, which take over the patient's natural breathing [3]. In recognition of its widespread impact, the World Health Organization officially declared COVID-19 a global pandemic [4].

Mechanical ventilation has a long history, dating back to the 18th century, but it wasn't until the 1950s that closed-loop ventilation systems were developed. Early versions employed basic proportional or proportional-integral controllers to regulate airflow into the lungs using mechanical valves and fans [5]. The advent of microprocessors revolutionized these systems, enabling more sophisticated closed-loop control schemes. Modern mechanical ventilators with closed-loop control mechanisms are categorized based on their interaction with the patient [6-8].

This Paper centers on developing a pressure-based ventilation controller classified under Class 2, which utilizes physiological parameters as the control variables rather than purely physical ones. Unlike Class 1 control loops, which do not incorporate patient feedback, Class 2 control loops are designed to adapt to patient-specific responses, aiming to maintain desired airway pressure levels.

The ongoing challenges presented by the COVID-19 pandemic underscore the importance of advancing respiratory support technologies. With ARDS being a common and often fatal complication, there is a critical need for ventilators that

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can adapt to the varying needs of patients. This research contributes to this field by proposing a robust and adaptive control mechanism that enhances the efficacy and safety of mechanical ventilation for patients with severe respiratory conditions.

The structure of this paper is as follows: The model of the ventilator is presented in the second section. The proposed robust fuzzy control system model is introduced in the third section. The simulation and analysis of the results are detailed in the fourth section. Finally, the conclusion is presented in the fifth section.

## II. MODEL OF VENTILATION PROCESS

The respiratory system model used in this paper is based on the blower-hose-lung system model presented in [2], combined with a single-compartment lung model obtained from [9-11]. The goal of this control system is to modify the observed pressure ($P_{aw}$) in accordance with the intended pressure ($P_{target}$), as illustrated in Eq. (1). In this arrangement, air enters the hose via the blower and subsequently into the lung. This is done to carry out the inhaling procedure. The patient then exhales air into the hose, some of which exits through the built-in leaking tube. The leaking tube prevents exhaled air from returning to the system during the following cycle. In this case, the mathematical model of the process may be written as Eqs. (2) to (5).

$$e = P_{target} - P_{aw} \tag{1}$$

$$Q_{pat} = Q_{out} - Q_{leak} \tag{2}$$

$$Q_{out} = {(P_{out} - P_{aw})}/{R_{hose}} \tag{3}$$

$$Q_{leak} = {P_{aw}}/{R_{leak}} \tag{4}$$

$$P_{pat} = {(P_{aw} - P_{lung})}/{R_{lung}} \tag{5}$$

$Q_{out}: Air\ flow\ coming\ out\ of\ the\ blower$

$Q_{pat}: Air\ flow\ entering\ the\ lung$

$Q_{leak}: Flow\ rate\ of\ leakage\ air$

$R_{hose}: Hose\ resistance$

$R_{lung}: Lung\ resistance$

$R_{leak}: Resistance\ of\ the\ leakage\ part$

To create a model of the state space of the considered system, the blower's output pressure ($P_{out}$) is considered the input, two variables, the measured pressure of the hose ($P_{aw}$) and the air flow rate of the inlet to the lung ($Q_{pat}$), are considered the output, and the air pressure value inside the lung ($P_{lung}$) is considered a state variable. By merging the blower system equations, the complete relations may be stated as Eqs. (6) to (11).

$$e = P_{target} - P_{aw} \tag{1}$$

$$\dot{x} = \begin{bmatrix} \dot{x}_b \\ \dot{p}_{lung} \end{bmatrix} = \begin{bmatrix} 0 & A_b \\ B_h C_b & A_h \end{bmatrix} \begin{bmatrix} x_b \\ p_{lung} \end{bmatrix} + \begin{bmatrix} B_b \\ 0 \end{bmatrix} p_{control} \tag{6}$$

$$y = \begin{bmatrix} P_{aw} \\ Q_{pat} \end{bmatrix} = C_h . p_{lung} + D_h C_b x_b \tag{7}$$

$$A_h = \frac{\frac{1}{R_{hose}} + \frac{1}{R_{leak}}}{R_{lung}.C_{lung}\left(\frac{1}{R_{lung}} + \frac{1}{R_{hose}} + \frac{1}{R_{leak}}\right)} \tag{8}$$

$$B_h = \frac{\frac{1}{R_{hose}}}{R_{lung}.C_{lung}\left(\frac{1}{R_{lung}} + \frac{1}{R_{hose}} + \frac{1}{R_{leak}}\right)} \tag{9}$$

$$C_h = \left[\frac{\frac{1}{R_{lung}}}{\left(\frac{1}{R_{lung}} + \frac{1}{R_{hose}} + \frac{1}{R_{leak}}\right)} - \frac{\frac{1}{R_{hose}} + \frac{1}{R_{leak}}}{R_{lung}\left(\frac{1}{R_{lung}} + \frac{1}{R_{hose}} + \frac{1}{R_{leak}}\right)}\right]^T \tag{10}$$

$$C_h = \left[\frac{\frac{1}{R_{hose}}}{\left(\frac{1}{R_{lung}} + \frac{1}{R_{hose}} + \frac{1}{R_{leak}}\right)} - \frac{\frac{1}{R_{hose}}}{R_{lung}\left(\frac{1}{R_{lung}} + \frac{1}{R_{hose}} + \frac{1}{R_{leak}}\right)}\right]^T \tag{11}$$

## III. ROBUST FUZZY CONTROL SYSTEM MODEL

In this part, the robust fuzzy system model is designed by using the sliding model control (SMC) algorithm. This model is able to provide proper tracking performance by creating stable closed-loop conditions for the mechanical ventilator. By combining fuzzy logic (FL) and sliding model control (SMC), system stability can be maintained to a suitable level against the occurrence of disturbances and uncertainties.

### *A. Slide Surface Modeling*

The proposed approach provides high robust capabilities against uncertainties and unwanted disturbances by integrating the fuzzy theory and the operation principles of the sliding model control method in the fuzzy controller. The main purpose of the fuzzy controller is to approximate the pressure control ($p_{control}$) in such a way that its error value is minimized with the ideal control input of the system ($u^*$) [12-14].

Since the number of fuzzy rules increases exponentially with the expansion of the number of inputs, therefore, the sliding surface is used as a function of the state variables, which is applied as an input to the fuzzy system. The slip surface entered as an input to the fuzzy system is designed in the form of Eq. (12).

$$s(t) = \dot{e}(t) + k_1 e(t) + k_2 \int e(t).dt \tag{12}$$

$$e(t) = p_t - p_{aw} \tag{13}$$

$e(t): Tracking\ error$

$k_2 ، k_1: Constants\ of\ positive\ gain$

The $k$ coefficients are also obtained from the Hurwitz polynomial calculation, which is expressed in the Eq. (14), and these coefficients are determined so that all the roots are placed on the left-hand side of the plane. The derivative of slip surface can also be expressed by Eq. (15). In the following, the structure of the used fuzzy system is described.

$$h(\lambda) = \lambda^{n-1} + k_{n-1}\lambda^{n-2} + \cdots + k_1 \qquad (14)$$

$$\dot{s}(t) = \ddot{e}(t) + k_1\dot{e}(t) + k_2 e(t) \qquad (15)$$

### *B. Fuzzy System Modelling*

The Fuzzification: The fuzzy membership function transforms the input data into a fuzzy vector. In this project, two inputs are given to the fuzzy controller, which are the error signal (e) and the error change signal $\Delta_e$, which is the error signal of the difference between the input designed by the sliding model and the output of the system. The error signals shown in Fig. (1) are normalized. Membership functions for output variables including $P_{lung}$, $P_{out}$ and $C_{lung}$ are shown in Fig. (2).

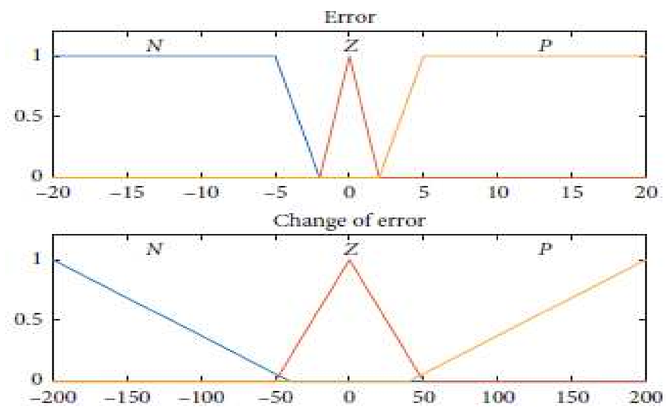


Figure 1. Membership functions for fuzzy system inputs.

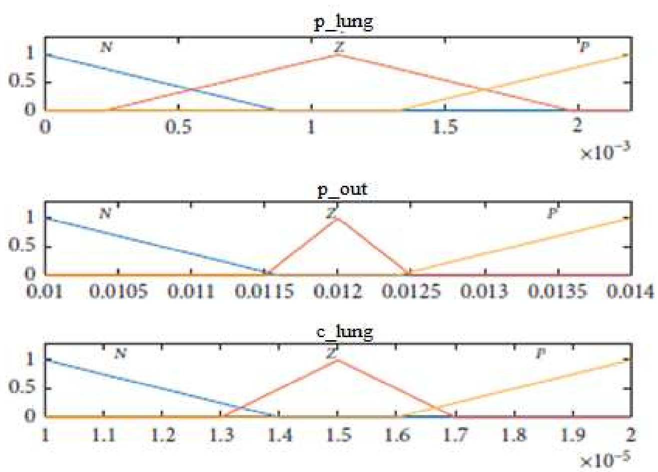


Figure 2. Membership functions for fuzzy system outputs.

Fuzzy rules: The values of $P_{lung}$, $P_{out}$ and $C_{lung}$ parameters are determined based on the following 4 basic rules:

- When e is large and $\Delta_e$ is negative, the system response is still far from the set point to move to the right. Therefore, $P_{lung}$ should be large, while $P_{out}$ and $C_{lung}$ should be small to approach the set point quickly.
- When e is negative and $\Delta_e$ is large, the system response exceeds the set point and the error is increasing. $C_{lung}$ is set large, while $P_{out}$ and $P_{lung}$ are set to limit too small.
- When e is small and $\Delta_e$ is positive, the system response is closed at steady state. Therefore, $P_{lung}$ should be large to reach steady state quickly. However, to reduce overshoot and avoid oscillation, $C_{lung}$ should be increased while $P_{out}$ should be decreased.
- When e is large and $\Delta_e$ is positive, the system response is excessive on the negative side. $C_{lung}$ should be large to reduce the error, while $P_{lung}$ and $P_{out}$ should also be increased.

Defuzzification: This part describes the process of converting a fuzzy inference result into a accurate output. The values of $P_{lung}$, $P_{out}$ and $C_{lung}$ parameters are set using fuzzy logic block signals based on the error change between them.

## IV. Performance Analysis and Discussion

The main objective of the proposed approach is to control the pressure level of the ventilation system within the standard range. The values of the mechanical parameters of the desired system are stated in Table 1. The ideal pressure is considered equal to 0.30 mbar. In Fig. 3, the relationship between the different components of the proposed approach is presented.

TABLE I. CHARACTERISTICS OF RESPIRATORY SYSTEM

| Parameters | Values |
|---|---|
| $R_{lung}$ | 0.005 (mbar/mL/s) |
| $R_{leak}$ | 0.06 (mbar/mL/s) |
| $R_{hose}$ | 0.0045 (mbar/mL/s) |

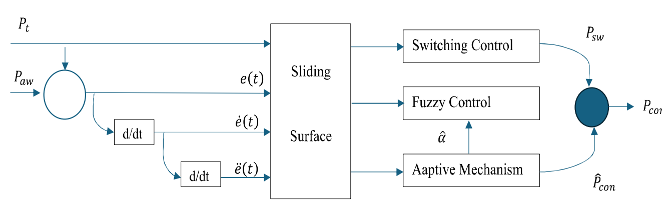


Figure 3. Block diagram of Respiratory control system.

MATLAB M-file and Simulink are used to simulated the respiratory system performance.

### *A. Controller Evaluation*

For simulation, two different lung compliance values are applied to the robust fuzzy controller. The first one with a constant of 20 mL/cm H2O throughout the inhalation and exhalation process, and the second one as a function of lung volume as shown in Fig. 4. In this condition, the lung compliance values are a function of lung volume. When the lung volume increase from 1, the lung compliance is increased from 5 to 20 and then it will be fixed at this point. After increasing the volume from 3, the lung compliance value is decreased until it reached to 5 as lower bound. The results in Fig. 5 show that tracking the pressure setpoint becomes more challenging as the lung compliance value changes. Under these conditions, the controller exhibits higher and more excessive oscillations compared to when the controller is simulated in the model with a constant lung compliance value. Then the robust fuzzy controller has been compared with the PID controller using the same parameters. This comparison is shown in Fig. 6.

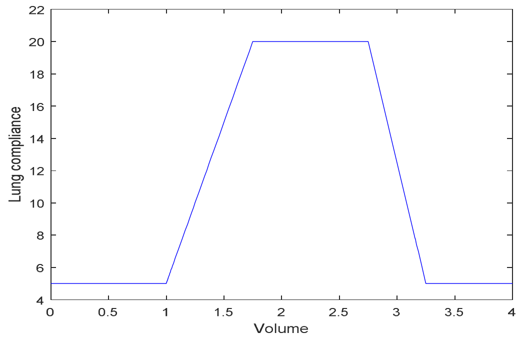


Figure 4. The compliance functions.

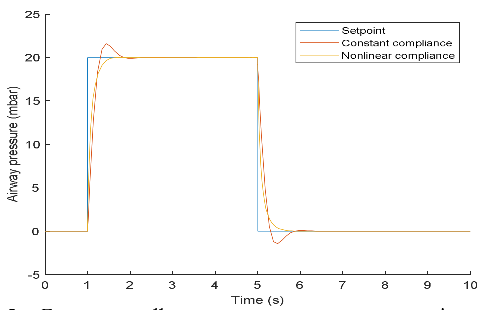


Figure 5. Fuzzy controller response in respiratory system with fixed adaptive value compared to nonlinear value.

In the figure above, the variations of airway pressure vs. time are shown. When constant compliance is used in modeling, the airway pressure value has overshoot and undershoot.

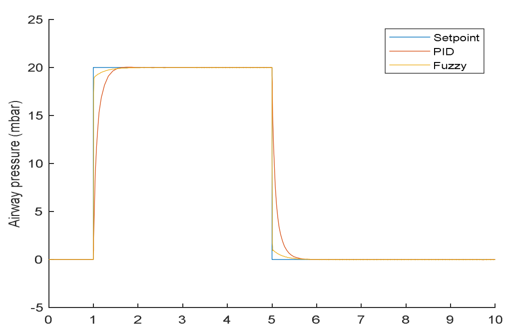


Figure 6. Comparison of response of fuzzy controller and PID controller in respiratory system.

With the use of nonlinear compliance model, this tracking is implemented in a smoother way. In the Fig. 8, the value of the airway pressure tracking is shown in two modes of using fuzzy logic controller and PID controller. As it can be seen, using the fuzzy logic has made a faster tracking with a lower amount of error.

*B. Performance Comparison of PID, Fuzzy, and Robust Fuzzy Controllers Under Disturbance Conditions.*

The PID controller, a traditional control approach, had an unusually short rise time, implying a quick initial reaction. Nonetheless, the overshoot was noticeably considerable, indicating that the system's response was much more than the intended value, which might be a symptom of stability problems. The fuzzy controller showed a compromise between a speedy reaction and moderate overshoot. Fuzzy logic is used to handle uncertainties and non-linearities in the system.

In respiratory system, we added a disturbance to the system so that we can see the limit of effective control used in. that disturbance represent as a function of the following equation:

$$D_{(t)} = k * (t - 1) * e^{-at} \quad (16)$$

Where; $k$ is a positive value, $t$ is time used in simulation, and a is small positive value, let us take $k = 0.1$, and $a = 1$.

According to that input function, the output of the system can be seen in Figs. 7 and 8.

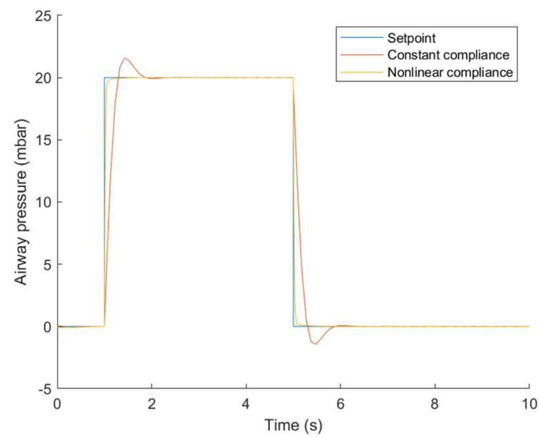


Figure 7. Fuzzy controller response in respiratory system compared to nonlinear value due to disturbance effect.

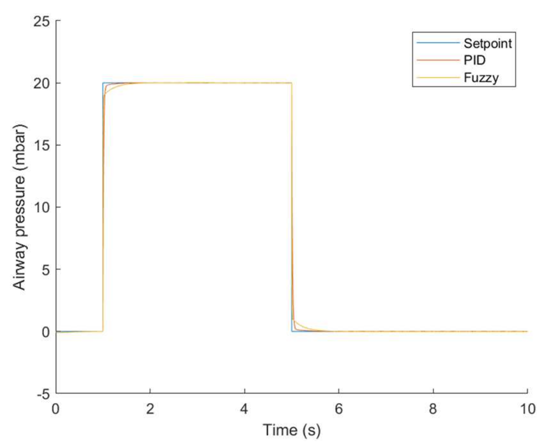


Figure 8. Comparison of response of fuzzy controller and PID controller in respiratory system due to disturbance effect.

In comparison to the conventional PID controller, the fuzzy controller offers a more controlled reaction to disturbances. Finally, the robust fuzzy controller showed the lowest overshoot among the fuzzy controllers, with a slightly longer rise time. This variant of the fuzzy controller is made to be more resilient to external disturbances and system fluctuations.

### *C. Results Comparison*

In this part, the output pressure tracking results according to the proposed approach are compared with the results obtained from the implementation of the PID and adaptive PID methods. In Fig. 6, it is assumed that the reference signal is changed as a step function and the result obtained in this situation shows that the adaptive fuzzy approach has a faster convergence rate. Comparison of tracking with variation as the step function is presented in Fig.9.

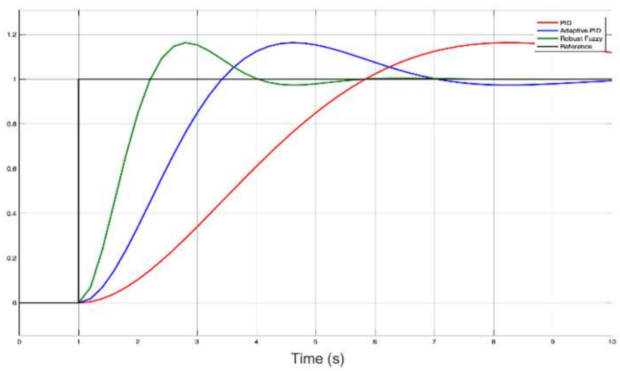


Figure 9. Comparison of tracking (variation as a Step function).

Following the tracking of the reference value by the robust fuzzy, PID and adaptive PID are shown in Fig. 10 when the variations is the same as ramp function. As you can see in this figure, the obtained results by using the robust fuzzy algorithm have the minimum error.

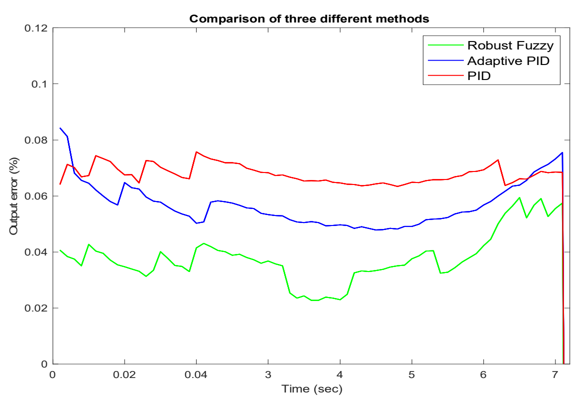


Figure 10. Comparison of tracking (variation as a Step function).

In Table 2 the values obtained from the simulations for the two modes of fixed compatibility value and non-linear compatibility value of the above evaluation criteria are shown. As can be seen in the table, the proposed method has a better performance compared to the PID controller. The values of the rise time, peak value, heave, minimum and maximum settlement for the adaptive PID controller are calculated as 0.0497, 20.0224, 1.8e3, 0.0210 and 0.0118 respectively. Also, the values of these criteria in the proposed method are 0.0418, 20.0278, 489.5598, 0.0116 and 0.0020 respectively, and these values for the normal PID controller are 0.0524, 21.5904, 1.9e4, 1.4448 and 0.0738 respectively. The results of the simulations show the superiority of the Robust Fuzzy controller method compared to the PID controller.

TABLE II. COMPARISON EVALUAION CRITERIA FOR PID & ROBUST FUZZY CONTROLLERS

| **Parameter** | **Method** | | |
|---|---|---|---|
| | ***Robust Fuzzy Controller*** | ***Adaptive PID Controller*** | ***PID Controller*** |
| Rise Time | 0.0418 | 0.0497 | 0.0524 |
| Peak Value | 20.0278 | 20.0224 | 21.5904 |
| Overshoot (%) | 489.5598 | 1.8e3 | 1.9e4 |
| Settling Min | 0.0116 | 0.0210 | 1.4448 |
| Settling Max | 0.0020 | 0.0118 | 0.0738 |

## V. CONCLUSION

The respiratory systems and ventilators used for specialized care purposes include two types of actuators: one for inspiration and the other for expiration. an inhalation actuator is a source of airflow, such as a piston actuator. during exhalation, positive end-expiratory pressure (peep) can be obtained using a pressure control valve (peep valve). in this project, the design of an innovative mechanical ventilator system has been studied. for this purpose, a fuzzy controller has been selected and in order to improve the stability of the system against disturbances, a sliding mode controller has also been used.

According to the robust surface and reaching laws for sliding mode control, there is no chattering/ oscillation appears in the response.

The effectiveness of the proposed approach has been simulated in two cases without disturbances and considering disturbances. Also, the obtained results have been compared with PID and adaptive PID systems.

The values of the rise time, peak value, heave, minimum and maximum settlement for these control mechanisms is calculated separately. According to obtained results, the risetime is improved by more than 18% and settling time is decreased more than 44%. The results of the simulations show the superiority of the Robust Fuzzy controller method compared to the PID controller.

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