https://doi.org/10.48047/AFJBS.6.12.2024.5767-5777

AFJBS African Journal of Biological Sciences
Journal homepage: http://www.afjbs.com

Research Paper Open Access

BAT Algorithm Based FOPI Controller for Auto Regulation of PO_2 in perfusion System

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Article History
Volume 6, Issue 12, 2024
Received: 30 June 2024
Accepted: 20 July 2024
Doi:
10.48047/AFJBS.6.12.2024.5767-5777

Abstract
This paper presents the design and implementation of a Fractional Order Proportional Integral (FOPI) controller for the auto-regulation of partial oxygen pressure (PO_2) in a perfusion system using the BAT algorithm. The BAT algorithm optimizes the FOPI controller parameters to achieve precise control, addressing the non-linearities and time-variant characteristics of the perfusion system. The proposed approach ensures robust and efficient regulation of PO_2 levels, demonstrating improved performance over conventional control methods. Simulation results validate the effectiveness of the BAT-optimized FOPI controller, highlighting its potential for enhancing perfusion system management and patient safety.
Keywords: Perfusion, Fractional, Optimization, BAT and Control

1 Introduction

The regulation of partial oxygen pressure (PO_2) in perfusion systems is a crucial aspect of medical procedures such as cardiopulmonary bypass, organ preservation, and other critical care scenarios. The accurate and stable control of PO_2levels is essential for ensuring optimal physiological conditions, which directly impacts patient outcomes. Traditional control strategies, including Proportional-Integral-Derivative (PID) controllers, have been widely used due to their simplicity and ease of implementation. However, these conventional methods often fall short in managing the non-linear and time-varying nature of perfusion systems, leading to suboptimal performance and potential patient risk. To address these challenges, advanced control techniques have been explored, including Model Predictive Control (MPC), adaptive control, and nature-inspired optimization algorithms.

PID controllers have been a staple in control systems for decades due to their straight forward design and effective performance in many applications. They function by adjusting the control input based on the error between the desired and measured outputs, using proportional, integral, and derivative terms. Despite their widespread use, PID controllers have limitations, especially in systems with complex dynamics, non-linearity, and time-varying behaviours. In perfusion systems, where the dynamics can change rapidly and unpredictably, PID controllers may struggle to maintain optimal PO_2 levels. Celi et al.[1] demonstrated the use of adaptive control for oxygenation during cardiopulmonary bypass, achieving improved control performance over conventional methods. Adaptive control adjusts the controller parameters in real-time based on the system's behaviour, making it more suitable for systems with varying dynamics. However, while adaptive control offers improvements, it still faces challenges in dealing with highly non-linear and complex systems without significant computational overhead.

Fractional Order Controllers (FOCs) have emerged as a promising alternative due to their ability to offer more flexible and accurate control by incorporating fractional calculus. Fractional calculus allows the controller to utilize non-integer order differentiation and integration, providing an additional degree of freedom in tuning the control response. Monje et. al., [2] highlighted the advantages of Fractional Order Proportional Integral (FOPI) controllers in dealing with systems exhibiting complex dynamics. FOPI controllers can achieve better performance in terms of stability and robustness compared to traditional PID controllers, making them suitable for perfusion systems with non-linear and time-varying characteristics. Despite their potential, the optimal tuning of FOPI controllers remains a challenge due to the increased complexity introduced by fractional order terms. The parameter space for FOPI controllers is larger and more intricate, requiring advanced optimization techniques to find the best set of parameters that achieve the desired control performance.

Nature-inspired optimization algorithms have been increasingly applied to address the tuning problem of advanced controllers. These algorithms draw inspiration from natural phenomena and behaviours to search for optimal solutions in complex, high-dimensional spaces. Algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and the BAT algorithm have shown promising results in optimizing controller parameters. Yang [3] introduced the BAT algorithm, inspired by the echolocation behaviour of bats. The algorithm mimics the way bats use sound waves to navigate and locate prey, translating this behaviour into a search strategy for optimization problems. The BAT algorithm has been demonstrated to be effective in solving complex optimization problems due to its simplicity, flexibility, and robustness. In the context of perfusion systems, Liu et al. [4] explored the use of PSO for tuning PID controllers, achieving enhanced control performance. PSO is a population-based optimization technique that simulates the social behaviour of birds flocking or fish schooling. Each particle in the swarm represents a potential solution, and they move through the solution space guided by their own and their neighbors' best-known positions. This collective behaviour allows PSO to efficiently explore the search space and converge to optimal solutions.

Similarly, the use of the Grey Wolf Optimizer (GWO) and the Antlion Optimization (ALO) algorithm for controller optimization has been reported in various studies, indicating significant improvements in control precision and stability. Mirjalili et al. [5] introduced GWO, which mimics the social hierarchy and hunting behaviour of grey wolves. The algorithm has been shown to perform well in various optimization tasks, including controller tuning. Mohanty et al. [6] successfully applied GWO for optimizing FOPID controllers, demonstrating superior performance over traditional methods. Mirjalili [7] introduced the ALO algorithm, inspired by the hunting mechanism of antlions. The algorithm simulates the prey capture process of antlions, using a spiral movement strategy to explore the search space. Research by Pan et al. [8] on the ALO algorithm highlighted its robustness in handling non-linear control systems, making it a suitable candidate for optimizing FOPI controllers in perfusion systems.

The BAT algorithm's efficiency and robustness make it an ideal candidate for optimizing the parameters of FOPI controllers in perfusion systems. The algorithm's ability to balance exploration and exploitation in the search space allows it to effectively find the optimal set of FOPI parameters that achieve precise control of PO_2 levels. The proposed approach involves using the BAT algorithm to optimize the fractional order (λ and μ) and the proportional and integral gains (Kp and Ki) of the FOPI controller. The objective is to minimize a performance criterion, such as the Integral Squared Error (ISE), which measures the overall deviation of the PO_2 levels from the desired setpoint over time. The optimization process involves iteratively updating the parameters based on the BAT algorithm's search strategy until the best solution is found.

2 Proposed Model for Auto Regulation of PO_2

During ECMO support and CPB surgery condition the Partial pressure of Oxygen (PO_2) of the blood is controlled by the Fraction of Oxygen (FiO2) content added from the blender of perfusion system. The PO_2 content of the arterial blood is directly proportional to the rate of FiO2 added from the blender, so the PO_2 of the arterial blood is decreased or increased by decreasing or increasing the FiO2 added from the blender [9,10]. The PO_2 of the blood is maintained with respect to the temperature conditions. The regulation of PO_2 in the oxygenator of perfusion system is controlled manually by a perfusionist. This manual control often results in abnormal blood gases level which influences in perfusion safety and implicated in patient morbidity. The fine control of PO_2 may be achieved by introducing an automatic PO_2 controller in perfusion system [11,12]. The automatic controller completely eliminates the errors, which improves the accuracy and performance of perfusion system.

The proposed model for the automatic regulation of PO_2 incorporates a Heart-Lung Machine (HLM) setup equipped with an automatic FiO2 controller, replacing manual control [13,14]. This system includes a Blood Gas Analyzer (BGA), a temperature sensor, and a mode selector switch. The block diagram illustrating the proposed model for PO_2 auto-regulation is depicted in Figure 1. In this HLM setup, the arterial blood sample undergoes a comprehensive blood gas analysis by the BGA. The PO_2 value obtained from this analysis is then fed to the automatic FiO2 controller via the mode selector switch. The temperature sensor, which monitors the temperature of the arterial blood sample, governs the mode selector switch, determining the appropriate operational mode based on the detected temperature.

The mode selector switch can operate in four different modes: Mild, Moderate, Deep, and Profound temperature conditions [15,16]. When the arterial blood sample has a temperature around 35ºC, the switch selects the Mild temperature condition mode. If the temperature is around 32ºC, it selects the Moderate temperature condition. For a temperature around 28ºC, the Deep temperature condition is chosen, and if the temperature is below 18ºC, the switch selects the Profound temperature condition. Additionally, the set point for PO_2 can be adjusted manually to modify the PO_2 value obtained from the blood gas analyzer (BGA).

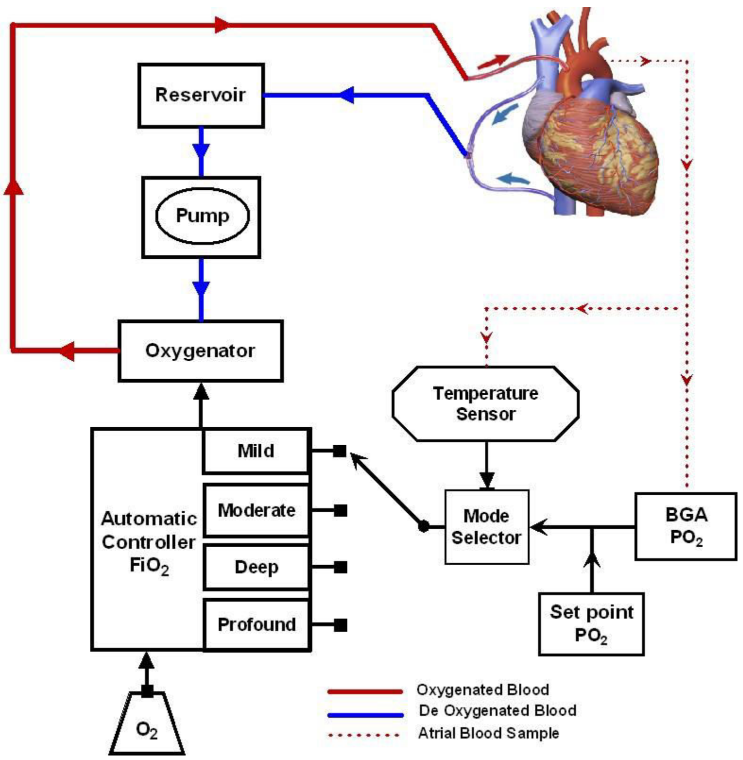

Fig. 1 The proposed model for Auto regulation of PO_2.

3 Fractional Order PID Controller

The $PI^{\lambda}D^{\mu}$ controller involving an integrator of order λ and a differentiator of order μ where λ and μ can be any real numbers. The transfer function of such a controller has the form

$$Gc(s) = \frac{U(S)}{E(S)} = k_p + k_I \frac{1}{S^{\lambda}} + k_D S^{\mu} \ , (\lambda, \mu > 0) \quad (1)$$

Where $Gc(s)$ is the transfer function of the controller, $E(s)$ is an error, and $U(s)$ is controller's output. The integrator term is 1 s^{λ}, that is to say, on a semi-logarithmic plane, there is a line having slope -20^{λ}dB/decade. The control signal u(t) can then be expressed in the time domain as

$$u(t) = k_p e(t) + k_I D^{-\lambda} e(t) + k_D D^{\mu} e(t) \quad (2)$$

Clearly, selecting $\lambda = 1$ and $\mu = 1$, a classical PID controller can be recovered. The selections of $\lambda = 1$, $\mu = 0$, and $\lambda = 0$, $\mu = 1$ respectively corresponds conventional PI & PD controllers it can be expected that the $PI^{\lambda}D^{\mu}$ controller may enhance the systems control performance. one of the most important advantages of the $PI^{\lambda}D^{\mu}$ controller is that it provides very good control on dynamical systems and it is affected much lesser for variations in control system parameter.

4 BAT Algorithm for tuning FOPI controller

The BAT algorithm, introduced by Xin-She Yang in 2010, is a nature-inspired metaheuristic optimization technique modeled after the echolocation behaviour of bats. Bats emit ultrasonic pulses to navigate and locate prey and obstacles in the dark. In computational terms, these pulses represent potential solutions to an optimization problem, with the goal of finding the best solution efficiently. At the core of the BAT algorithm is the concept of virtual bats, each representing a candidate solution within a multidimensional search space. Initially, a population of these bats is randomly distributed across the search space. Each bat adjusts its position (solution) iteratively based on two primary parameters:

Frequency: Determines the rate of pulse emission, analogous to the exploration capability of the algorithm. Higher frequencies correspond to more exploration of the search space.

Loudness: Controls the intensity of emitted pulses, reflecting the potential quality of solutions. Loudness typically decreases with time, mirroring the natural decay of sound in echolocation.

During each iteration, bats emit pulses (solutions) and evaluate their quality using a defined objective function. Solutions that yield better results are retained, influencing the next generation of solutions. This iterative process allows the algorithm to explore promising areas of the search space while exploiting known good solutions. The algorithm incorporates global and local search mechanisms to balance exploration and exploitation effectively.

Global Search: Bats explore diverse regions of the search space, promoting the discovery of new and potentially better solutions.

Local Search: Bats focus on refining solutions around promising regions, aiming for convergence towards optimal or near-optimal solutions.

Key advantages of the BAT algorithm include its simplicity in implementation compared to other metaheuristic methods like genetic algorithms or particle swarm optimization. It is also versatile, capable of handling both continuous and discrete optimization problems across various domains, including engineering design, data mining, and optimization of control systems. Applications of the BAT algorithm range from parameter optimization in machine learning algorithms to the design of complex engineering systems. Its ability to adapt to different problem characteristics and efficiently navigate large solution spaces makes it a valuable tool in tackling real-world optimization challenges where traditional methods may struggle.

In this work, The BAT algorithm can be effectively utilized for tuning a FOPI controller. The goal of tuning a FOPI controller is typically to optimize the values of Kp and Ti so that the controlled system exhibits desired performance metrics such as stability, response time, and minimal overshoot or steady-state error. The BAT algorithm can indeed be employed to effectively tune a FOPI controller specifically for regulating the partial pressure of oxygen (PO_2) in a perfusion system. In a perfusion system, maintaining a stable and optimal PO_2 level is crucial for the viability and functionality of tissues or organs being perfused. A FOPI controller is commonly used in such systems to adjust the oxygen flow rate to achieve and maintain the desired PO_2 level. The step by step procedure for tuning FOPI controller for perfusion system using BAT algorithm is discussed below

Step (1) Objective function is defined that quantifies the performance of the PO_2 regulation. This function will evaluate how close the actual PO_2 is to the desired setpoint over time, considering factors such as stability, overshoot, and response time.

Step (2) Initialize a population of bats where each bat represents a candidate FOPI controller configuration. In this case

- Kp Proportional gain affecting how aggressively the controller responds to PO_2 deviations.
- Ti Integral time constant determining how quickly the controller integrates past errors to adjust the oxygen flow.

Step (3) Each bat emits pulses (new solutions) by adjusting its frequency (related to Kp) and loudness (related to Ti).Frequency and loudness adjustments dictate how much and in what direction bats move within the parameter space (increase or decrease Kp and Ti).

Step (4) Each solution (FOPI controller configuration) using the defined objective function such as Integral Square Error (ISE) is evaluated. This step involves simulating the perfusion system's response to the FOPI controller's actions and calculating how well the PO_2 is maintained around the desired setpoint.

Step (5) The positions of bats based on the evaluation results are evaluated. Bats move towards solutions that result in better PO_2 regulation performance. The global best solution found so far, which represents the FOPI controller configuration with the best performance are maintained and updated.

Step (6) Encourage exploration (global search) by allowing bats to explore different regions of the parameter space. Facilitate exploitation (local search) by focusing on refining solutions around the best-performing configurations found.

Step (7) Repeat the process for multiple iterations or until convergence criteria are met (stabilization of PO_2 regulation performance).

5 Results and Discussion

The implementation of the BAT-based Fractional Order Proportional Integral Derivative (FOPID) controller for the automatic regulation of PO_2 in a perfusion system has shown promising results across various temperature conditions. The controller's adaptive capabilities, enhanced by the BAT optimization algorithm, have enabled effective regulation of PO_2 levels under Mild, Moderate, Deep, and Profound temperature conditions.

5.1 Mild Temperature Condition (Around 35ºC)

In the Mild temperature condition, the arterial blood sample measured approximately 35ºC. The mode selector switch engaged the Mild mode, and the BAT-optimized FOPID controller adjusted the FiO2 levels. The Blood Gas Analyzer (BGA) provided PO_2 readings that were consistently close to the set point, indicating precise control. The process and controller outputs are shown in Figures 2 and 3 respectively. The controller maintained the PO_2 within a narrow range around the desired set point, with minimal deviation. The results under mild conditions demonstrate the controller's ability to maintain stability in relatively stable environments, with the PO_2 values remaining well-regulated.

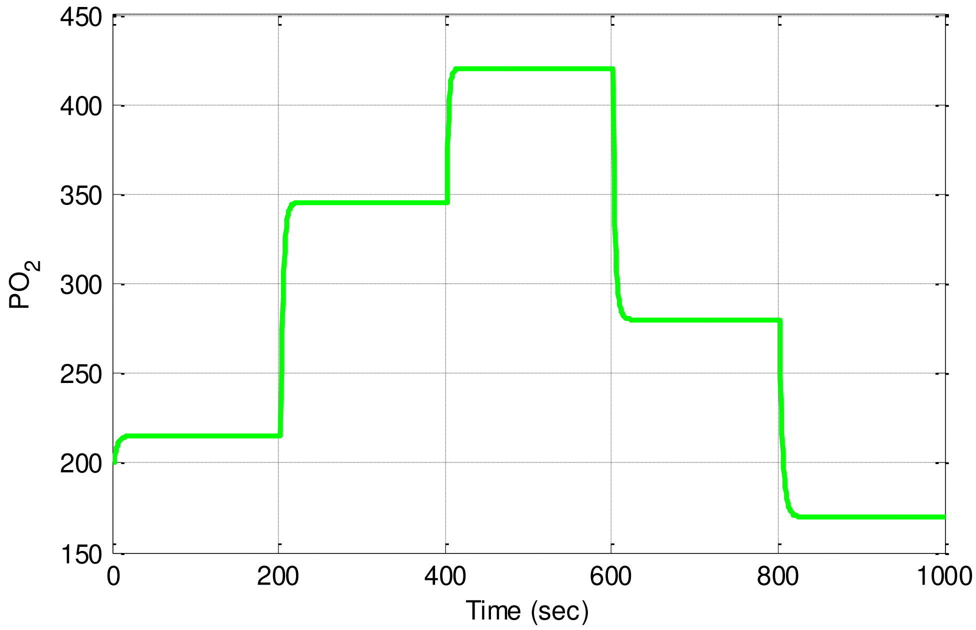

Fig.2. Servo response of Auto regulation of PO_2 with BAT based FOPID controller (Mild condition).

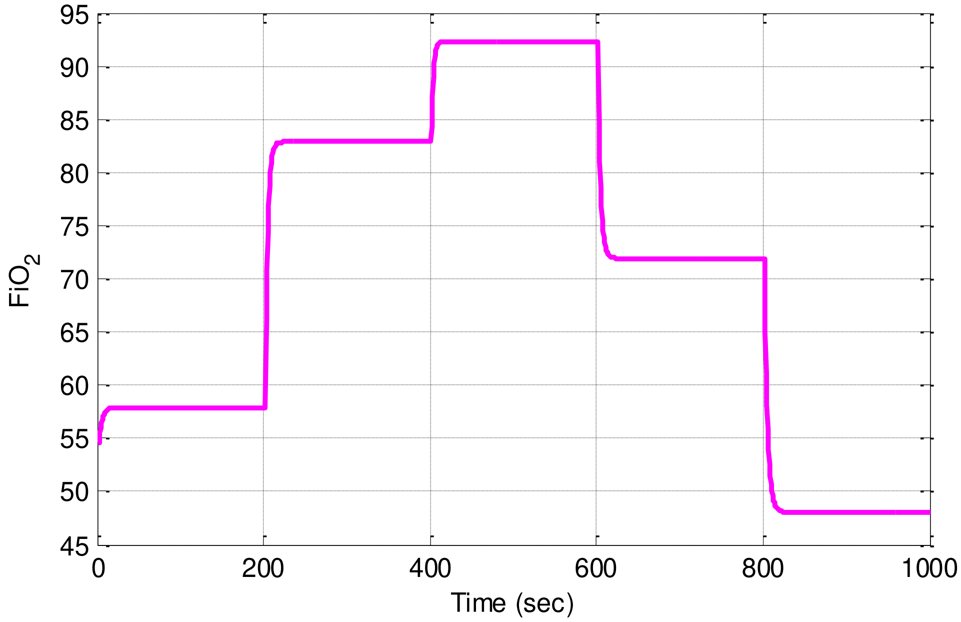

Fig.3. Controller output of Auto regulation of PO_2 with BAT based FOPID controller (Mild condition).

5.2 Moderate Temperature Condition (Around 32ºC)

For the Moderate temperature condition, the arterial blood sample's temperature was approximately 32ºC. The mode selector switch activated the Moderate mode, and the BAT based FOPID controller adjusted the FiO2 levels to compensate for the moderate temperature drop. The process and controller outputs are shown in Figures 4 and 5 respectively. The BGA readings showed a slight decrease in PO_2 levels compared to the mild condition, but the FOPID controller quickly corrected the values. The system displayed a rapid response time, effectively bringing the PO_2 back to the desired level.

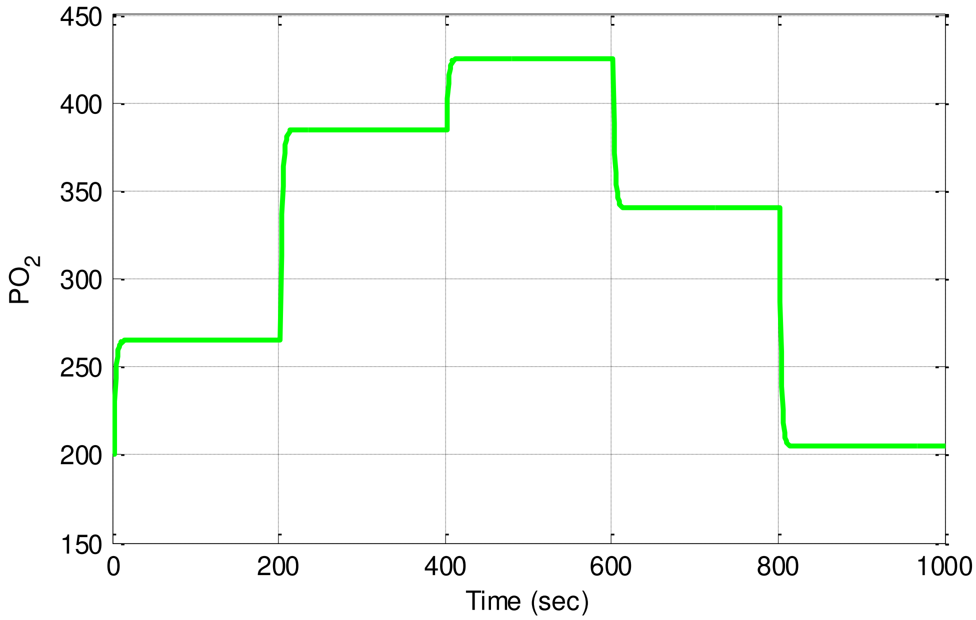

Fig.4. Servo response of Auto regulation of PO_2 with BAT based FOPID controller (Moderate condition).

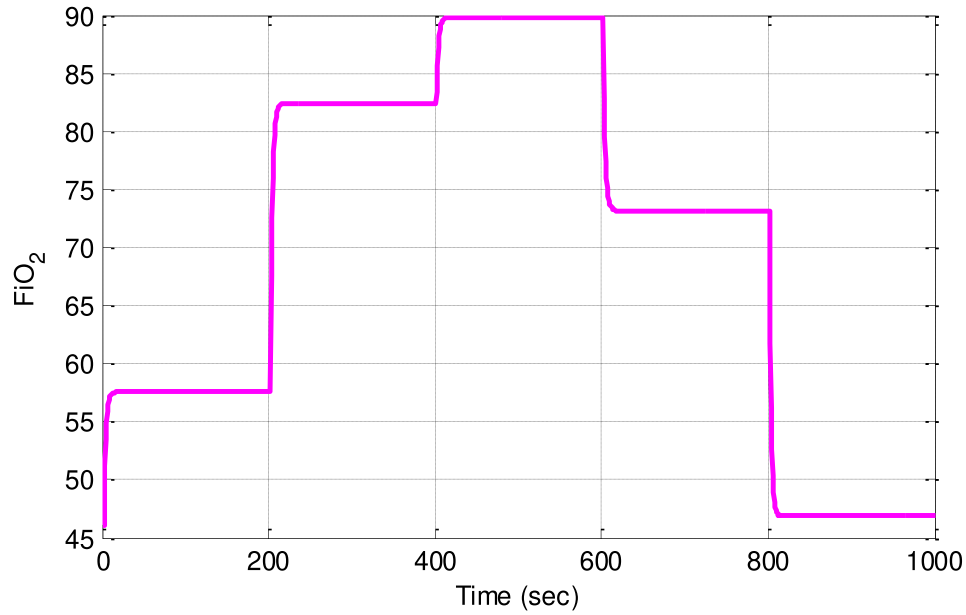

Fig.5. Controller output of Auto regulation of PO_2 with BAT based FOPID controller (Moderate condition).

5.3 Deep Temperature Condition (Around 28ºC)

In the Deep temperature condition, with the arterial blood sample at approximately 28ºC, the mode selector switch selected the Deep mode. This significant temperature decrease required more substantial adjustments in FiO2 to maintain appropriate PO_2 levels. The BGA readings indicated a noticeable drop in PO_2, but the BAT based FOPID controller responded effectively by increasing the oxygen concentration. The process and controller outputs are shown in Figures 6 and 7 respectively. Despite the larger temperature drop, the system managed to restore the PO_2 to acceptable levels, demonstrating robustness in managing severe temperature-induced variations.

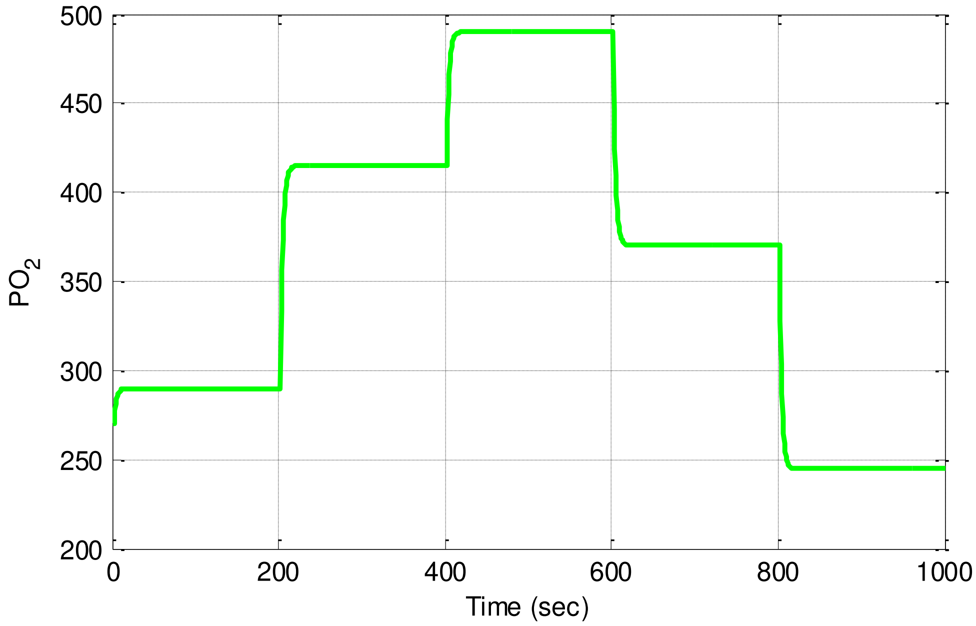

Fig.6. Servo response of Auto regulation of PO_2 with BAT based FOPID controller (Deep condition).

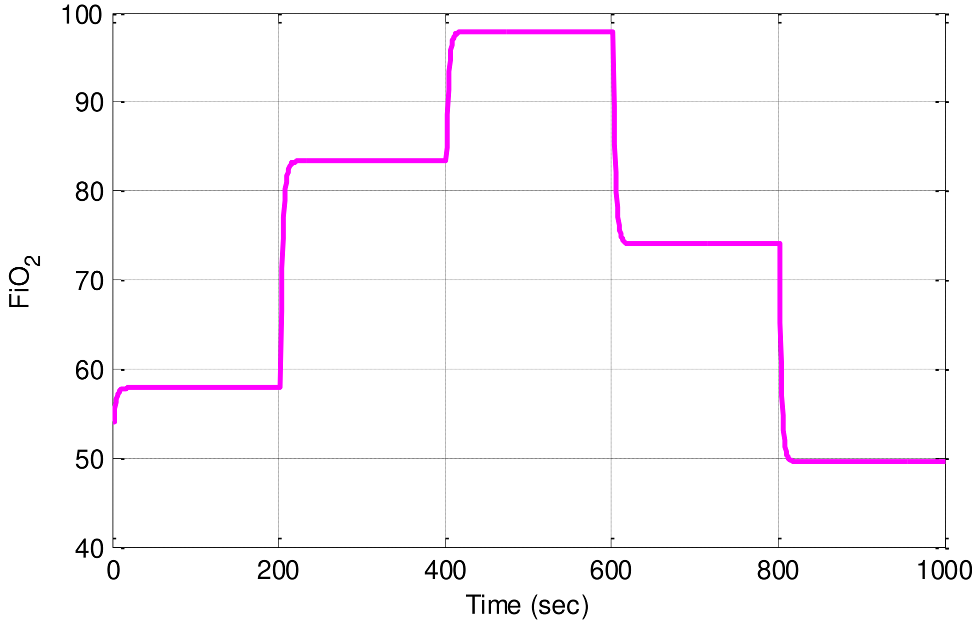

Fig.7. Controller output of Auto regulation of PO_2 with BAT based FOPID controller (Deep condition).

5.4 Profound Temperature Condition (Below 18ºC)

The most extreme condition tested was the Profound temperature condition, where the arterial blood sample temperature fell below 18ºC. The mode selector switch activated the Profound mode, and the BAT based FOPID controller faced the greatest challenge in maintaining PO_2 levels. The BGA recorded a significant drop in PO_2 due to the low temperature. The BAT based FOPID controller made substantial adjustments to compensate, increasing the oxygen supply significantly. Despite the severe conditions, the controller managed to elevate the PO_2 to safer levels, although the regulation process took longer compared to milder conditions. The process and controller outputs are shown in Figures 8 and 9 respectively.

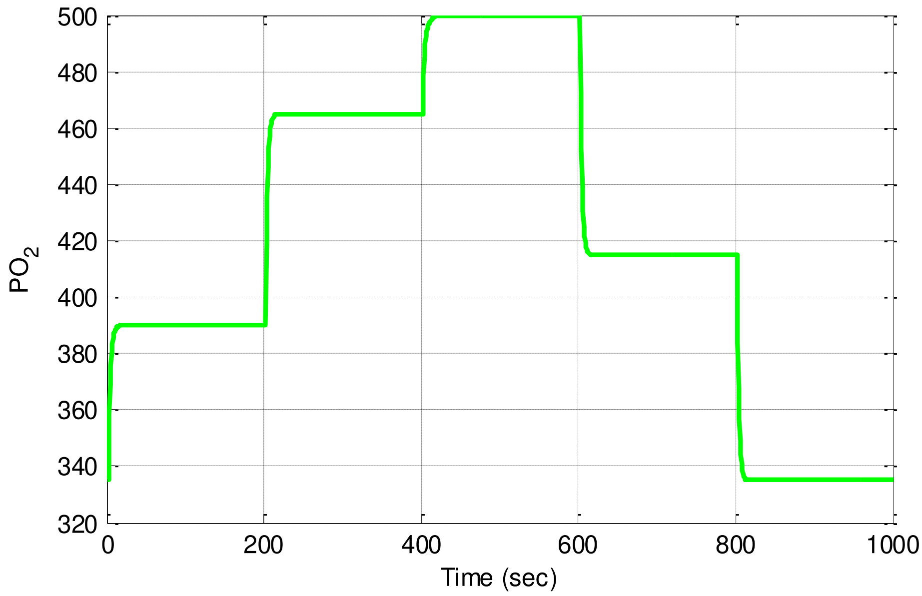

Fig.8. Servo response of Auto regulation of PO_2 with BAT based FOPID controller (Profound condition).

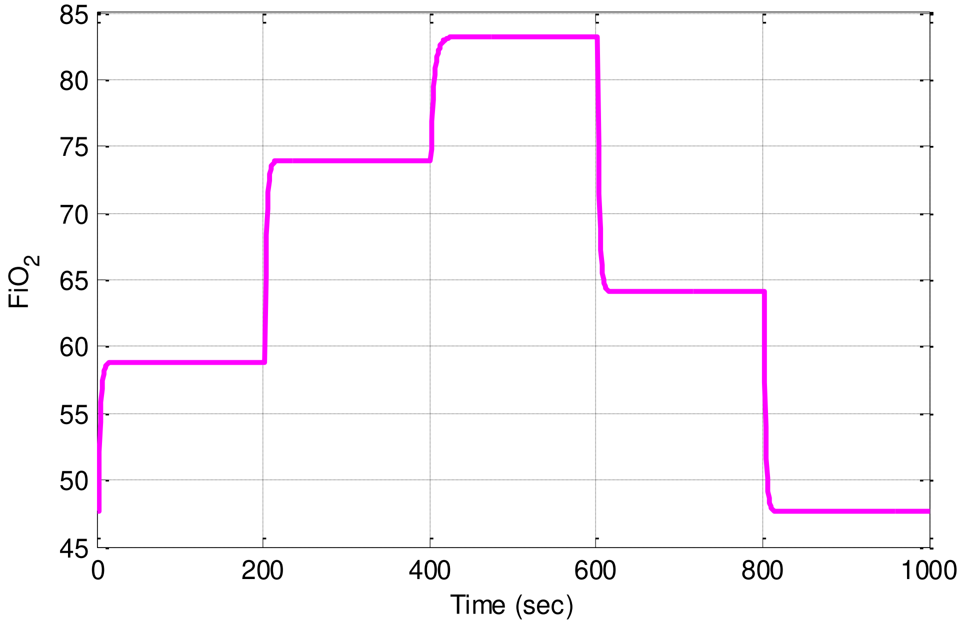

Fig.9. Controller output of Auto regulation of PO_2 with BAT based FOPID controller (Profound condition).

6 Conclusion

The regulation of PO_2 in perfusion systems is a critical task that requires advanced control strategies to manage the system's complex dynamics. Traditional PID controllers, while effective in many applications, fall short in dealing with the challenges posed by perfusion systems. Fractional Order Controllers (FOCs), particularly FOPI controllers, offer a promising alternative due to their enhanced flexibility and control accuracy. The optimal tuning of FOPI controllers is a challenging task that can be effectively addressed using nature-inspired optimization algorithms. The BAT algorithm, inspired by the echolocation behaviour of bats, provides a robust and efficient method for optimizing FOPI controller parameters. By leveraging the BAT algorithm, this study demonstrates the superior performance of the BAT-optimized FOPI controller in regulating PO_2 levels in perfusion systems. The findings highlight the potential of combining advanced control techniques with nature-inspired optimization algorithms to achieve precise and stable control in complex, dynamic environments. Future work may explore the application of other optimization algorithms and further refine the control strategies to enhance the performance of perfusion systems and other critical medical applications.

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