FOPI Controller for Blood Pressure Regulation using Hippopotamus Algorithm

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Abstract. Blood pressure readings indicate the force the heart exerts on arterial walls while pumping blood. Maintaining mean arterial blood pressure during surgeries is crucial to control excessive bleeding. Vasodilating drugs like Sodium Nitroprusside (SNP) are used to lower blood pressure, but their required dosage and effects vary significantly depending on the patient's condition. This necessitates continuous monitoring and precise drug delivery. To achieve this, a controller is designed. The proposed FOPI controller is designed using a simple graphical approach based on the maximum sensitivity criterion with a fixed maximum sensitivity (γ), ensuring adequate phase margin (ϕ_m) and gain margin (G_m) for stability. The FOPI parameters are optimized as a function of minimizing integral absolute error (IAE), integral squared error (ISE), and integral time absolute error (ITAE) using the hippopotamus optimization algorithm. It is a metaheuristic algorithm that aims to find the optimal values by mimicking the behavior of Hippopotamuses in the wild. This study aims to evaluate the robustness and performance improvements of the proposed design compared to existing control strategies. A MATLAB environment was used for the simulation of the system and the implementation of the algorithm.

Keywords: Mean Artial Blood Pressure · Hippopotamus Algorithm · FOPI · H_∞ criteria · Integral Error

1 Introduction

Maintaining mean arterial blood pressure (MABP) during surgery is crucial. Blood pressure depends on cardiac output and peripheral resistance. Vasodilating drugs like sodium nitroprusside (SNP) lower blood pressure by reducing peripheral resistance. SNP's effects require careful control of infusion rate and duration to avoid toxicity. Postoperative patients are particularly vulnerable; excessive blood pressure reduction can cause adverse effects, including shock. Thus, precise infusion rate control is essential. Clinical SNP administration is challenging due to patient variability and the need for controlled drug release. Automatic drug delivery systems are needed to adjust infusion rates and maintain desired blood pressure levels [1].

Sheppard et al. developed a computer-based control system, but it didn't incorporate patient sensitivity [2]. These early controllers lacked adaptability to real-world disturbances, including surgical stimuli.

Adaptive controllers were developed to address these limitations. Slate and Sheppard proposed a model-based adaptive controller considering patient sensitivity [3]. Internal model control (IMC) offered improvements in steady-state accuracy, settling time, and overshoot and IMC-tuning showed superior robustness ~~[4]~~, and the IMC filter effectively rejected disturbances [5]. While optimal IMC had some advantages, PID controllers offered shorter settling ~~times~~ [6]. IMC-based PID controllers further improved response characteristics. Fractional-order PID controllers also showed promise. Optimization strategies have gained prominence to tune the parameters for these controllers. Heuristic and metaheuristic methods are used to tune controller parameters. Algorithms like particle swarm optimization, multi-strategy modified INFO algorithm, logarithmic spiral search-based arithmetic algorithm, novel hybrid approaches, whale optimization algorithm, human-inspired algorithms, and seeker optimization algorithm are used. a Genetic algorithms are also employed to optimize FO PID parameters [7]. The paper aimed to optimize FOPI controller Parameters using Hippopotamus Optimization Algorithm (HOA) based on graphical approach. The motivation to use HOA is motivated by the inherent behavior of group of hippopotamus in the wild. This approach is defined using a three-phase model which mimics the behavior of different types of hippos in the group and updating their position in rivers or ponds, predator defense strategies and evasion methods that are mathematically modeled [8].

IMC had larger settling time, hence PID controller was tuned to offer shorter setlling time

Heurestic (examples_ and Metaheuristic (examples)

IMC ke baare me Optimal IMC se comparison FOPID pe aa jaye fir mera FOPI

This paper aims to design a FOPI controller the search area is defined using H inf criteria based graphical approach and then the final parameters are tuned by HOA. (7-8) lines.

the main contribution are as follows- (4-5 points) 1) 2 stage FOPI controller designed 2) Find area by graphical approach 3) Used HOA to tune parameters minimize integral erros. 4) Results (comparisons) ///// ek aur paragraph defining the sections (4 lines)

2 Patient Response Model

Slate et al gave a model

~~Slate et al. [?]~~ investigated the impact of SNP infusion on patients by analyzing five parameters that exhibit significant variability in ~~mean arterial blood pressure~~ MABP in response to the drug, ~~using correlation analysis and pseudo-random binary signals~~.

The transfer function model used by Slate is:

$$P(s)\;\frac{\Delta P_d(s)}{I_n(s)} = \frac{Ke^{-T_{id}s}(1+\alpha e^{-T_{cd}s})}{\tau s+1} \tag{1}$$

where $\Delta P_d(s)$ represents the change in MABP (mmHg), $I_n(s)$ is the drug infusion rate (ml/hr), K denotes the drug sensitivity (mmHg/ml/hr), α is the recirculation constant, τ is the time constant (sec), T_{id} represents the initial time delay (sec), and T_{cd} corresponds to the recirculation time delay (sec). All time constants are expressed in seconds, and patients are classified into three categories based on their sensitivity to the drug, as shown in Table 1.

Biological systems are inherently influenced by disturbances ~~[9]~~. To achieve greater accuracy, these disturbances should be incorporated into the system model. Enbiya [6] developed a Simulink model to represent these disturbances.

FIgure wapas laga do

3 Controller Design

we are going to design FOPI controller for which, we are first using H inff criteria on a PI controller to find the search space for the HOA

~~This paper proposes a fractional-order Proportional-Integral (FOPI) controller.~~ The control structure using this FOPI control structure is shown in Fig. 1.

controller

Table 1. Parameter Values of Patients

Parameter	Sensitive	Normal	Insensitive
K (mmHg/(ml/hr))	-9	-0.7143	-0.1786
α	0	0.4	0.4
T_{id} (sec)	20	30	60
T_{cd} (sec)	60	30	45
τ (sec)	75	30	40

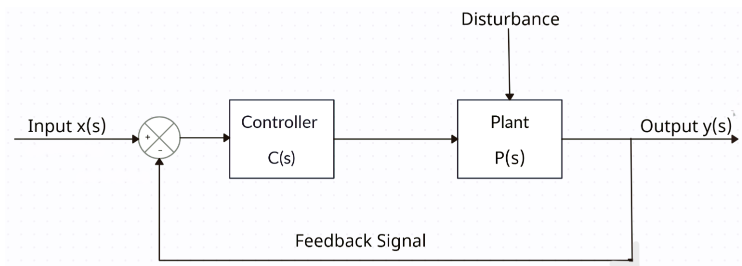

Fig. 1. Proposed Control Structure.

The objective of this research is to tune the parameters of the FOPI controller to achieve precise tracking of the patient model output to the desired setpoint ~~(30 mmHg)~~. We employ the ~~Hippopotamus Optimization Algorithm~~ (HOA) to minimize the error, specifically using Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE) as cost functions. The optimization process involves searching for the optimal proportional gain (K_p) and integral gain (K_i) of the FOPI controller. This search is conducted within a region determined by H_∞ criteria-based loop shaping approach. The fractional order (λ) of the FOPI controller is explored within the range of 0 to 2 by the HOA. The main objectives of the controller are to ensure that:

Introduction me jayega yaha se hat ke

1. Settling time should be less than 400 sec
2. Setpoint is -30mmHg
3. Overshoot should be less than 7mmHg
4. Steady State error should be less than 3mmHg

Ye results me jayega
(ALI SIR KO CORRECT NAHI KARNA HAI)

4 H_∞ Criterion

Result me jayega kaise kaise kaam kiye hai

which is based on max sensitivity defined as-(sir ke paper me se)

The H_∞ ~~loop shaping approach~~ is a robust control design technique that converts a control problem statement to a mathematical optimization problem. This approach balances performance and stability in the presence of model uncertainties, making it particularly useful for designing FOPI controllers in complex systems like the human body. H_∞ control is crucial for blood pressure regulation due to its inherent robustness, which allows it to handle patient-specific sensitivities, varying physiological responses, and external disturbances. Furthermore, it

~~which is used to find the 2D ki vs kp Search space for HOA using graphical approach.~~

effectively manages time delays inherent in the body's response to drugs, optimizes the trade-off between performance (e.g., settling time) and robustness, and maintains stability across a range of conditions, preventing excessive blood pressure fluctuations. To apply the H_∞ criteria on the human body plant, we have taken its equation :

$$\xcancel{P(s) = \frac{Ke^{T_{id}s}(1+\alpha e^{T_{cd}s})}{\tau s+1}} \tag{2}$$

And we are taking a PI controller defined as in frequency domain

$$C(j\omega) = K_p - \frac{K_i}{j\omega} \tag{3}$$

Considering the plant spilliting the plant model in real and imaginary part gives us

$$P(j\omega) = P_r(\omega) + jP_i(\omega) \tag{4}$$

yaha pe lamda add hone wala hai

And the maximum sensitivity equation

$$\left|\frac{1}{1+P(s)C(s)}\right|_\infty < \gamma \tag{5}$$

Putting the values of $P(s)$ and $C(s)$ in the equation gives us

$$\left|1 + (P_r(\omega) + jP_i(\omega))\left(K_p - \frac{jK_i}{\omega}\right)\right| > \frac{1}{\gamma} \tag{6}$$

Solving and rearranging the equation and substituting the values of $P_r(\omega)$ and $P_i(\omega)$ gives us the equation of an ellipse. given below

$$\frac{(K_i - C_1(\omega))^2}{a^2} + \frac{(K_p - C_2(\omega))^2}{b^2} > 1 \quad (13) \tag{7}$$

where

$$C_1(\omega) = -\frac{\omega^2 P_i(\omega)}{|P(j\omega)|^2}, \qquad C_2(\omega) = -\frac{P_r(\omega)}{|P(j\omega)|^2}$$

$$a(\omega) = \frac{\omega}{\gamma|P(j\omega)|}, \qquad b(\omega) = \frac{1}{\gamma|P(j\omega)|}$$

The ellipses from these equations are plotted in MATLAB. From the region bounded yet outside the ellipses, we will select a range of (K_i, K_p) and then use hippopotamus optimization algorithm in that range to select the parameters for our FOPI controller which minimizes our integral error cost functions.

with added lambda taken frrom 0 to 2 , that region is the search space for HOA,

5 Hippopotamus Optimization Algorithm (HOA)

HOA ke baare me, aur uska flowchart de dena. aur us flowchart ka variable change karne ki jarurat nahi padegi.

The ~~Hippopotamus Optimization Algorithm~~ (HOA) is a metaheuristic algorithm inspired by the social behavior of hippopotamuses. It simulates their interactions within a herd, including position updates, defense against predators, and escape mechanisms. HOA balances exploration (searching diverse areas) and exploitation (refining solutions in promising regions) to find optimal solutions.

flowchart me number of hippos aur iterations bhi bata dena hai

5.1 Initialization and Mathematical Modeling

~~HOA is population-based.~~ Each hippopotamus represents a potential solution, and their positions in the search space correspond to variable values. The initial population is randomly distributed within defined bounds:

$$x_{i,j} = lb_j + r \cdot (ub_j - lb_j), \quad i = 1, 2, \ldots, N, \quad j = 1, 2, \ldots, m$$

where $x_{i,j}$ is the position of the i-th hippopotamus in the j-th dimension, lb_j and ub_j are the lower and upper bounds, r is a random number between 0 and 1, N is the population size, and m is the number of variables.

5.2 Phase 1: Position Update (Exploration)

This phase models the hippos' movement within their territory. The dominant male's position influences the herd. Male hippopotamuses update their positions as follows:

apostrophe s hatana hai har jagah se

$$x_{i,j}^{M\_hippo} = x_{i,j} + y_1 \cdot D_{hippo} - I_1 \cdot x_{i,j} \tag{8}$$

where D_{hippo} is the position of the dominant hippopotamus, and I_1 is a random integer (1 or 2). Female and immature hippopotamuses, who often stay close to their mothers, update their positions based on their distance from the dominant hippo and a time-dependent factor T:

$$x_{i,j}^{FB\_hippo} = \begin{cases} x_{i,j} + h_1 \cdot D_{hippo} - I_2 \cdot M_{Gi}, & T > 0.6 \\ x_{i,j} + k_2 \cdot M_{Gi} - D_{hippo}, & r_6 > 0.5 \\ lb_j + r_7 \cdot (ub_j - lb_j), & \text{otherwise} \end{cases} \tag{9}$$

where M_{Gi} represents the mean position of a group of hippopotamuses, and $T = \exp(-t/T)$ with t being the current iteration and T the maximum number of iterations. The updated positions are chosen based on a comparison of fitness values:

$$x_i = \begin{cases} x_i^{M\_hippo}, & F_{M\_hippo}^i < F_i \\ x_i, & \text{otherwise} \end{cases} \tag{10}$$

$$x_i = \begin{cases} x_i^{FB\_hippo}, & F_{FB\_hippo}^i < F_i \\ x_i, & \text{otherwise} \end{cases} \tag{11}$$

where F_i is the fitness value of the i-th hippopotamus.

5.3 Phase 2: Defense Against Predators (Exploration)

This phase models the hippos' defensive behavior. When a predator is detected, the hippos move to defend the herd. The predator's position is defined as:

$$\text{Predator}_j = lb_j + r_8 \cdot (ub_j - lb_j) \tag{12}$$

The distance between a hippo and the predator is:

$$\mathbf{D} = |\text{Predator}_j - x_{i,j}|. \tag{13}$$

The hippos' defensive movement is given by:

$$\chi_i^{\text{HippoR}} = \begin{cases} \mathbf{RL} \oplus \text{Predator}_j + f \cdot (c - d \cdot \cos(2\pi g)) \cdot (1 - \mathbf{D})\,, & F_{\text{Predator}_j} < F_i, \\ \mathbf{RL} \oplus \text{Predator}_j + f \cdot (c - d \cdot \cos(2\pi g)) \cdot \left(1 - \frac{\mathbf{D}}{2} + r_9\right), & F_{\text{Predator}_j} \geq F_i, \end{cases} \tag{14}$$

where **RL** is a random vector following a Lévy distribution. If the hippo's fitness worsens, it is replaced.

5.4 Phase 3: Escape from Predators (Exploitation)

This phase models the hippos' escape to water when threatened. Local search bounds are defined as:

$$\text{lb}_j^{\text{local}} = \frac{\text{lb}_j}{t}, \quad \text{ub}_j^{\text{local}} = \frac{\text{ub}_j}{t}$$

The hippos' movement towards water is:

$$x_{i,j}^{\text{HippoE}} = x_{i,j} + r_{10} \cdot \text{lb}_j^{\text{local}} + s_1 \cdot \left(\text{ub}_j^{\text{local}} - \text{lb}_j^{\text{local}}\right)$$

The updated position is chosen based on fitness. The algorithm simplifies by not categorizing the hippos into different groups.

5.5 Steps for Designing the Controller

The following steps outline the process for designing the controller:

1. Define the plant model with suitable patient parameters and the value of γ = 2 then plot the ellipses for the closed loop function.
2. Select the range of (K_p, K_i) from the region outside yet bounded by the ellipses. And choose a range for λ preferably between 0 and 2.
3. Run the HO ~~(Hippopotamus Optimization)~~ algorithm in MATLAB on the specified range.
4. If the final result is achieved at the boundary ~~you specified~~ of the region specified then increase the range and rerun the algorithm.
5. ~~Compare the performances with different error settings and analyze the response.~~

ellipses ka figure daal dena hai aur usme rectangular region dikha dena hai

6 Simulation Results and Discussion

The HOA was used to find the suboptimal parameters by simulating the controller in SIMULINK, which minimized the cost function (ITAE and IAE). Its range was chosen from the boundary made by the ellipses taking γ=2 with some additional regions around it too, in cases the algorithm reaches the boundary of the area provided. Table 2 lists the tuned parameters by HOA.

Table 2. Tuned Parameters of FOPI Controller using HOA.

Patient Type	Cost Function	K_p	K_i	λ
Sensitive	IAE	-0.12644	-0.0022915	1.0505
	ITAE	-0.103	-0.0023486	1.0295
Nominal	IAE	-1.6097	-0.009579	1.0919
	ITAE	-1.0323	-0.012667	1.0169
Insensitive	IAE	-3.9225	-0.023564	1.0627
	ITAE	-3.6109	-0.023459	1.0562

hippopotamus section ke andar jayega ye table aur upar ka paragraph bhi

yaha pe aayega ki ref point, matlab simulation ka . to evaluate effectiveness of proposed controller, for sens model the step response is shown in fig 2 and the control effort is shown in fig 3, and it can be observed that the settling time is reduced by.

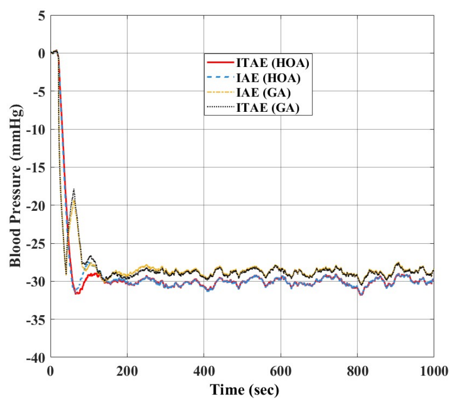

Fig. 2. Sensitive Patient Results.

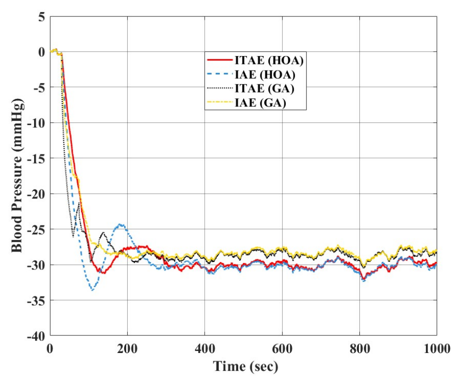

Fig. 3. Nominal Patient Results.

The results demonstrate effective blood pressure regulation for all patient types. The HOA successfully optimized the FOPI controller parameters, achieving minimal ITAE and IAE, as shown in Figures 2, 3, and 4. We achieved a smaller settling time and less steady-state error along with reduction in the Error values as shown in Table 3.

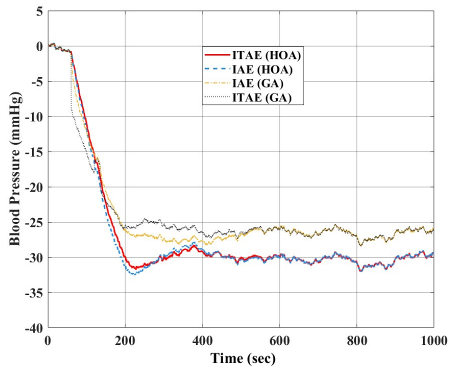

Fig. 4. Insensitive Patient Results.

Table 3. Performance Indices for Patient Model

parameter (GA)

Patient Type	Performance Index	FOPID (Reference)	FOPI (Proposed)
Sensitive	IAE ($\times 10^3$)	2.36	1.3
	ITAE ($\times 10^6$)	0.59	0.23
Nominal	IAE ($\times 10^3$)	3.2	2.4
	ITAE ($\times 10^6$)	0.73	0.35
Insensitive	IAE ($\times 10^3$)	6.2	4.0
	ITAE ($\times 10^6$)	1.94	0.49

settling time, steady state error, overshoot

7 Conclusion

is `

A FOPI controller was used to control the blood pressure of three different patient models. A H_∞ criteria based graphical approach was used to find the range for the parameters of the controller and the parameters were tuned by hippopotamus optimization algorithm. The proposed controller is easy to implement in real time, the parameters to be designed is less, hence it has a smaller computational burden. The controller used a 2-D graphical approach of a K_p vs K_i graph to get the range of parameters. To get even better results, future research aims to use other techniques to estimate the range of the Kd parameters and fine tune it using HOA to design a FOPID controller that gives much better results. Add the analysis

Points me jayega

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