Robust PI Controller Design using Graphical Approach for Blood Pressure Regulation

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Introduction

- During surgeries, to maintain the mean arterial blood pressure, a vasodilating drug is given to lower the blood pressure to control excessive bleeding.
- Its required amount and effects greatly vary on the type of patient, so we need to monitor the effects, too, continuously.
- Such precise drug-delivery systems require a controller to work on the patient response model.
- We will use a Graphical Approach based on Maximum Sensitivity with a PI controller.
- Compare the results of the PI controller to the FOPID controller of the reference paper.

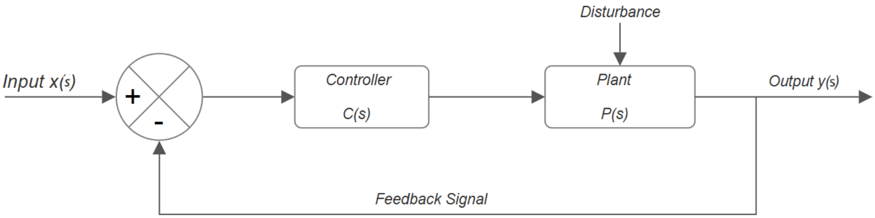


Figure: 1 : Control system Diagram.

Where:
P(s): Transfer function of the plant considered
C(s): Controller of the Plant

Problem Formulation

- For suboptimal control, maximum gain of S(sensitivity function) for frequency $\omega \in [0, \infty) \leq \gamma$ (max sensitivity).
- When $\gamma \geq 1$, ensures phase margin $\phi_m = 2\sin^{-1}\left(\frac{1}{2\gamma}\right)$ degrees, and gain margin $G_m = 20\log\left(\frac{\gamma}{\gamma-1}\right)$ dB.
- So we design a controller minimizing S, i.e.

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

- The following equation of a human body plant for a drug response is considered for testing the method:

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

Designing a Controller using using Graphical Approach based on Maximum Sensitivity

- Substituting $s = j\omega$, in $P(s)$ so that, $e^{Tj\omega} = \cos(T\omega) - j\sin(T\omega)$ gives:

$$P_r(\omega) = \frac{K}{t^2\omega^2 + 1}\left(\cos(T_i\omega) + a\cos(T_i\omega + T_c\omega) - t\omega\sin(T_i\omega) - at\omega\sin(T_i\omega + T_c\omega)\right) \tag{3}$$

$$\omega P_i(\omega) = \frac{-K}{t^2\omega^2 + 1}\left(\sin(T_i\omega) + a\sin(T_i\omega + T_c\omega) + t\omega\cos(T_i\omega) + at\omega\cos(T_i\omega + T_c\omega)\right) \tag{4}$$

- **A PI controller $C(s) = K_p - \frac{K_i}{s}$ has been used.**

- Considering $P(j\omega) = P_r(\omega) + j\omega P_i(\omega)$ and $C(j\omega) = K_p - \frac{K_i}{j\omega}$, eqn(1) is written as:

$$\left|(1 + P_r(\omega)K_p + P_i(\omega)K_i) + j\left(\omega P_i(\omega)K_p - P_r(\omega)\frac{K_i}{\omega}\right)\right| \geq \gamma, \qquad (5)$$

- On simplifying and rearranging equation (5) in the parametric form of an ellipse gives:

$$K_i = C_i(\omega) + h(\omega)\cos(\theta)$$
$$K_p = C_p(\omega) + k(\omega)\sin(\theta)$$
$$\theta \in [0, 2\pi)$$

Where:

$$C_i(\omega) = -\frac{\omega^2 P_i(\omega)}{|P(j\omega)|^2}, \quad C_p(\omega) = -\frac{P_r(\omega)}{|P(j\omega)|^2},$$

$$h(\omega) = \gamma|P(j\omega)| \quad k(\omega) = \frac{\gamma|P(j\omega)|}{\omega},$$

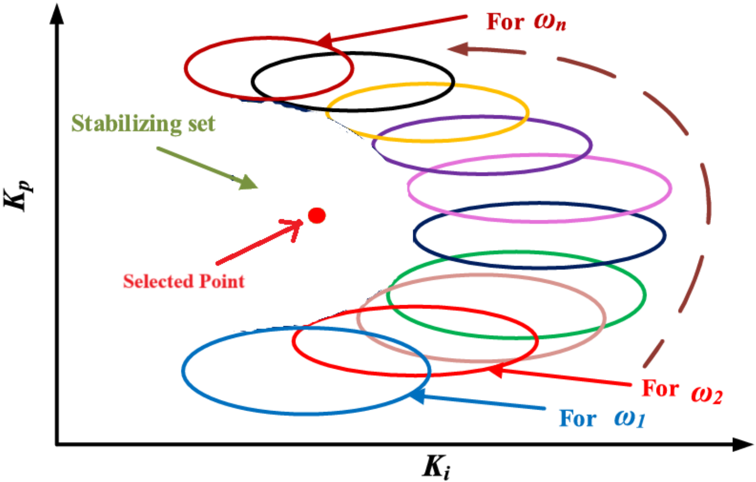
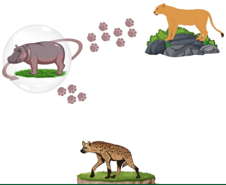


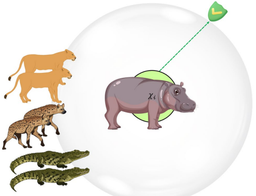
Figure: 2 : Stabilizing PI controller region for plant.

- From the figure 2, we can see that the region outside the ellipses is stable, and values of K_p and K_i can be selected from it.

Hippopotamus Optimization Algorithm

- HO is a novel metaheuristic algorithm inspired by the inherent behavior of hippopotamuses.
- It simulates defense and evasion strategies against predators and performed location updates.
- It has the advantages of high accuracy, strong local search ability, and good practicality.
- It has significant research value in improving global search, enhancing local development capabilities, and avoiding local optima.
- It works in three phases namely, exploration, predator defense (also exploration), and escaping predators (exploitation).





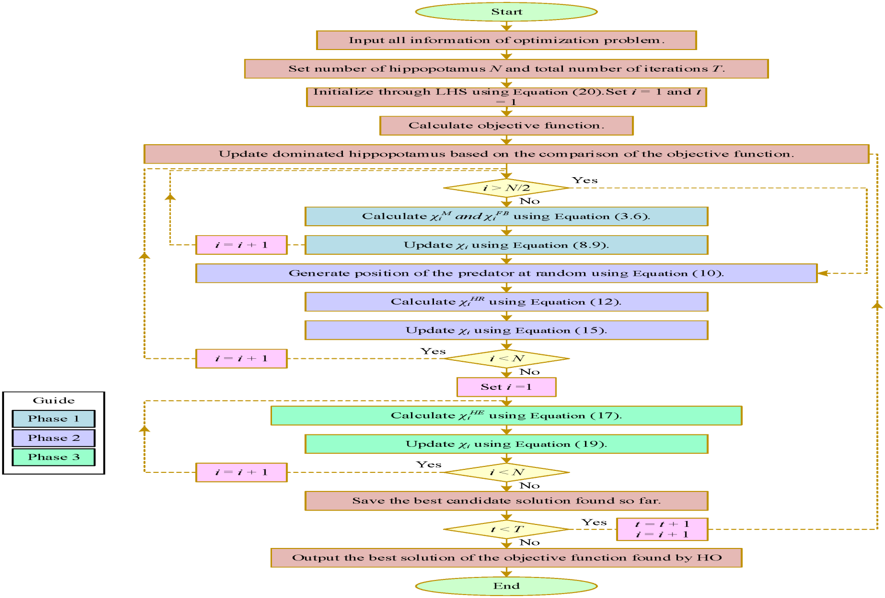


Figure: 3: Flowchart of Hippopotamus algorithm.

Testing on a Sample Equation 1

Values for a sensitive patient are: $K = -9$ mmHg/(ml/hr), $\alpha = 0$, T_{id} (sec) $=$ 20, T_{cd} (sec) $= 30$, τ (sec) $= 30$, $\omega = [10^{-6}, 0.68]$

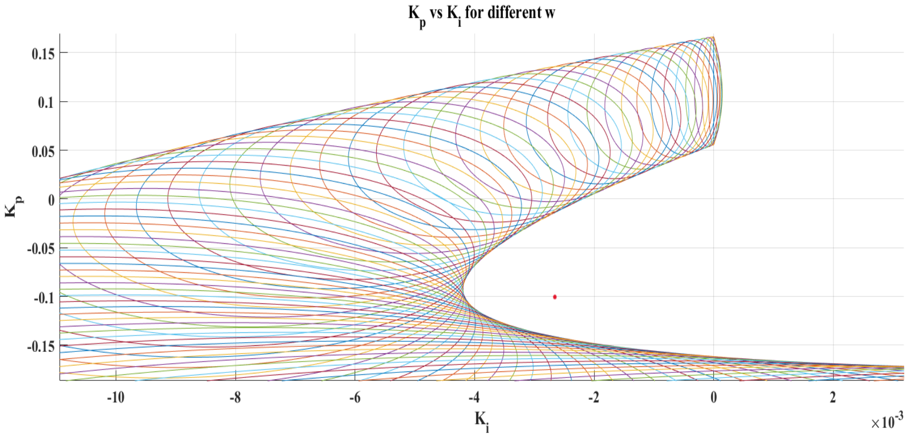


Figure: 3: Ellipses for Sensitive patient.

Testing on a Sample Equation 2

Values for a nominal patient are: $K = -0.7143$ mmHg/(ml/hr), $\alpha = 0.4$, T_{id} (sec) $= 30$, T_{cd} (sec) $= 45$, τ (sec) $= 40$, $\omega = [10^{-6}, 0.68]$

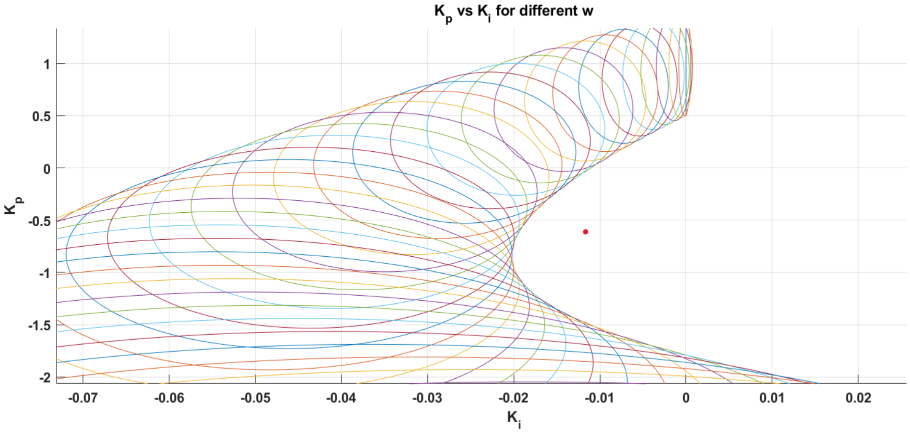


Figure: 4: Ellipses for Nominal patient.

Region selection and Optimization

- A rectangular region is selected from the region bounded by the ellipses and given as input to the HO Algorithm to find the best K_p, K_i, and λ.
- The Nyquist plot is analysed for encirclements of the critical point $-1 + j0$ to determine the closed-loop stability of the PI controller.

Sensitive ITAE FOPID Parameters

$K_p = -0.048,\ K_i = -0.0047,\ \lambda = 0.92,\ K_d = -0.9754,\ \mu = 0.6695$

Nominal IAE FOPID Parameters

$K_p = -0.1534,\ K_i = -0.0054,\ \lambda = 0.8584,\ K_d = -9.266,\ \mu = 0.4605$

Simulation and Comparison

Figure 6 and 7 compare the FOPID and proposed FOPI controllers' performances.

Proposed Controller Performance comparison (Sensitive)

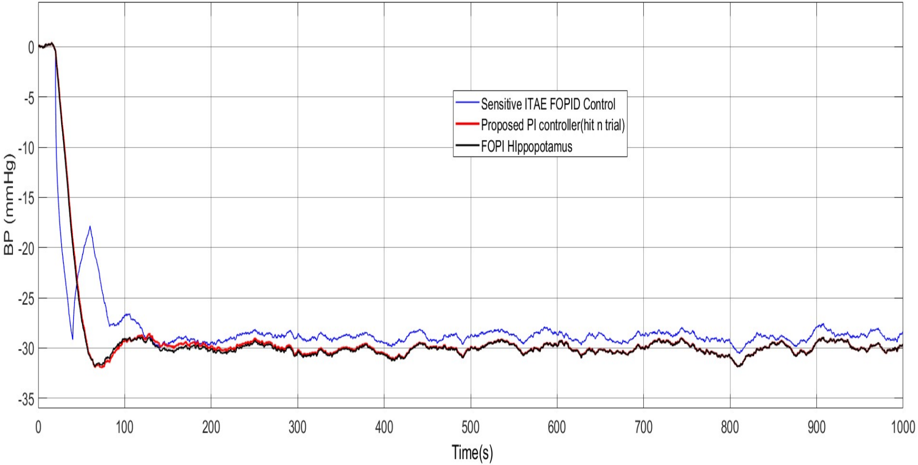


Figure: 6: Comparison between FOPID and proposed FOPI controller performance. Best score of proposed HO FOPI=1485886 vs FOPID controller=2164722. Parameters: Kp= -0.11422 , Ki=-0.002594, lambda=1.0361

Proposed Controller Performance comparison (Nominal)

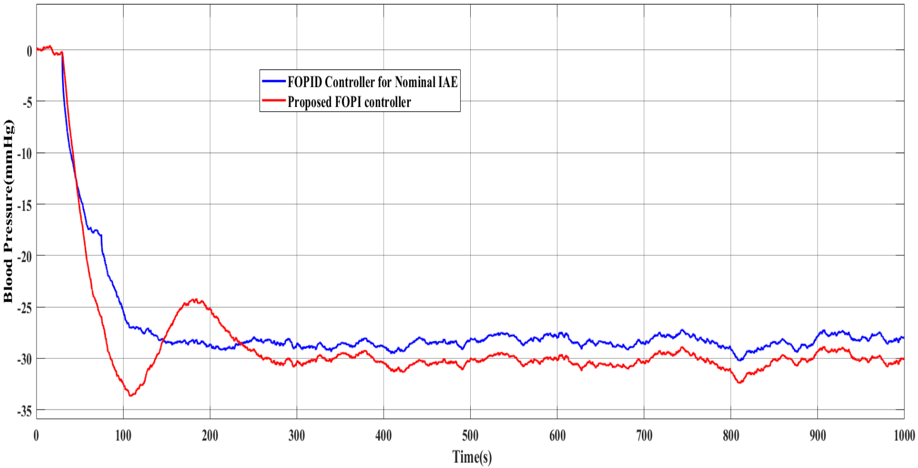


Figure: 7: Comparison between FOPID and proposed FOPI controller performance . Best score of HO FOPI controller 2406 vs FOPID in reference paper 3289, Parameters- Kp= -1.6097, Ki= -0.009579 lambda= 1.0919

Nyquist plot (Sensitive Patient)

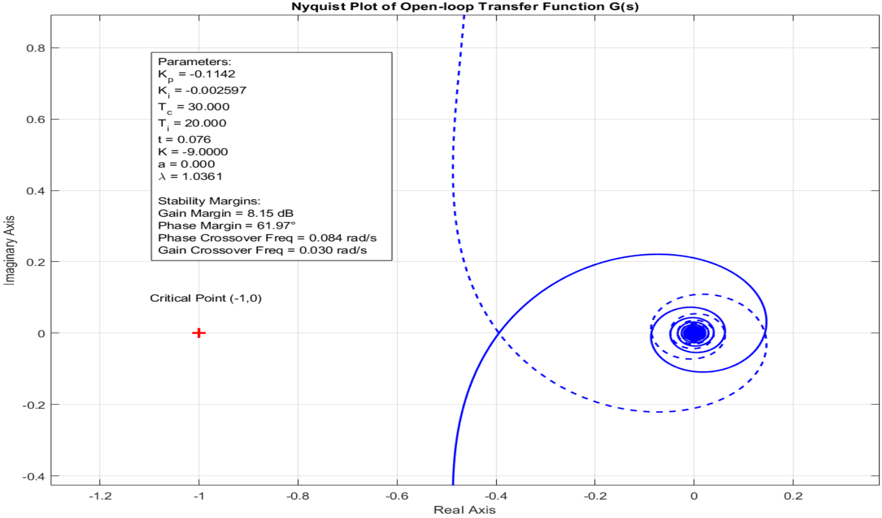


Figure: 8: Nyquist Plot for checking the Stability at the selected Kp and Ki.

Nyquist plot (Nominal Patient)

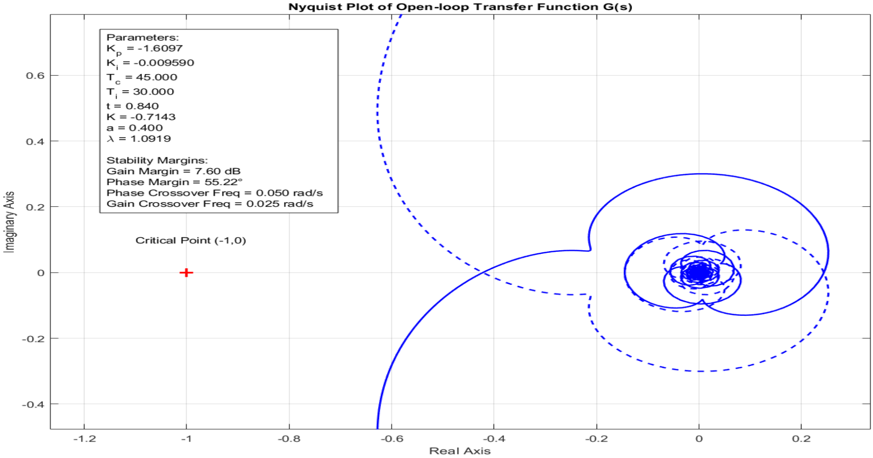


Figure: 9: Nyquist Plot for checking the Stability at the selected Kp and Ki.

10% Uncertanity in Plant Parameter (Sensitive)

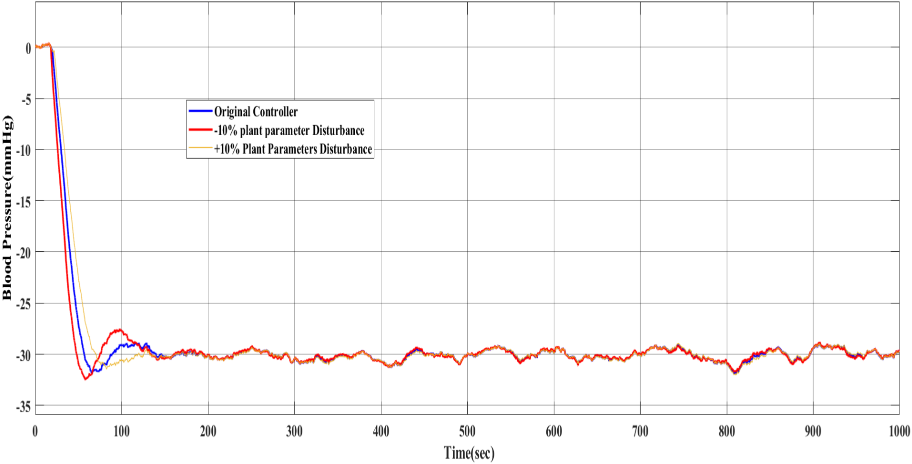


Figure: 10: Step Response with ±10% uncertainty in Sensitive Patient.

10% Uncertanity in Plant Parameter (Nominal)

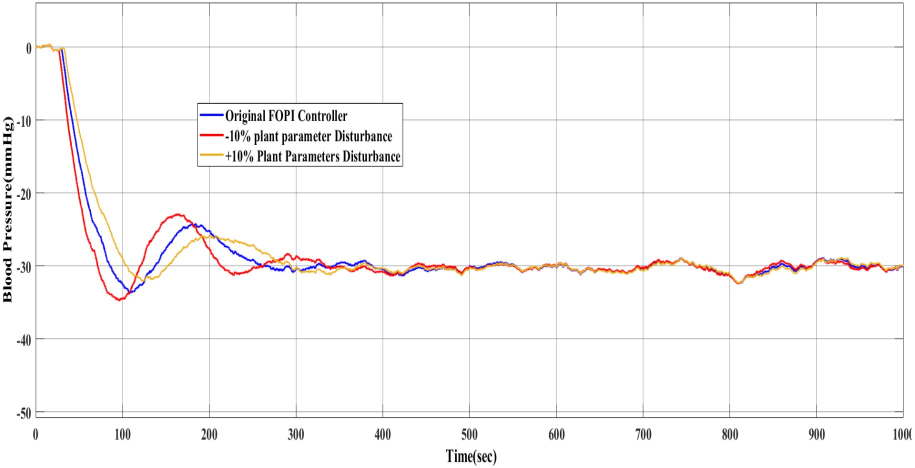


Figure: 11: Step Response with ±10% uncertainty in Normal Patient.

Results and Conclusion

Patient Type	Error Type	Kp	Ki	λ	Kd	μ	Error
Sensitive	ITAE (Proposed)	-0.11422	-0.002594	1.0361	--	--	1485886
	ITAE (Reference)	-0.048	-0.004	0.9637	-1.8578	0.9799	2164722
Nominal	IAE (Proposed)	-1.6097	-0.009579	1.0919	--	--	2406
	IAE (Reference)	-0.6	-0.02	0.965	-5.5	0.65	3289

Figure: 12: Comparison Table.

- FOPI controller designed using **H∞ criterion** for a system with delay.
- Controller parameters selected through **Hippopotamus Optimization algorithm** from plotted region.
- Stability, closed-loop gain, and phase margins analyzed using **Nyquist plot**.
- Achieved **less steady-state error** and **33% less error.**
- **FOPI controller** ensures easy real-time implementation.
- Fewer parameters reduce the **computational burden**.

References

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