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Intelligent Flow Rate Regulation Using Hybrid Metaheuristic PID Optimization and ANFIS Control

1
Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

in

Control & Instrumentation

by

Saumya Tiwari

(2k24/C&I/23)

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CANDIDATE'S DECLARATION

I, **Saumya Tiwari**, Roll No. **2K24/C&I/23**, M.Tech (Control & Instrumentation), hereby declare that the project Dissertation titled **“Intelligent Flow Rate Regulation Using Hybrid Metaheuristic PID Optimization and ANFIS Control”** which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is not imitated from any source without proper citation and is authentic. This work has not beforehand formed the root for the award of any Degree, Diploma, Fellowship, Associateship or any other similar title or acknowledgment.

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I, hereby certify that the Project Dissertation titled **“Intelligent Flow Rate Regulation Using Hybrid Metaheuristic PID Optimization and ANFIS Control”** is submitted by **Saumya Tiwari, Roll No. 2K24/C&I/23**, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology is a testimony of the project work carried out by the student under my supervision. To the best of my awareness this work has not been submitted in part or full for any Degree or Diploma to this University or to a different place.

Place: **New Delhi**Date: **May 2026****Prof. Mini Sreejeth**

(Professor, DTU)

ABSTRACT

This thesis discusses some of the advanced control techniques applied in flow rate regulation in industry, including optimization based tuning and intelligence based modeling. There are two major parts to the thesis. In the first one, the Proportional-Integral-Derivative (PID) controller is optimally tuned using Hybrid Ant Colony Optimization (ACO)-Particle Swarm Optimization (PSO). The combination of the strengths of the two optimization algorithms (global search ability of PSO and local search abilities of ACO) enables optimal tuning of the PID controller. Consequently, there will be improved dynamic performance with low settling time, reduced overshoot and stability. In the other part, an Adaptive Neuro-Fuzzy Inference System (ANFIS) model is used as an intelligent data-driven model for flow rate control. Training of the ANFIS model is done using system's input-output data. ANFIS can adaptively control flow rates and has good performance characteristics under different operating conditions and external disturbances. Comparison of performances of the optimized PID controller and ANFIS controller are made using various performance measures like rise time, settling time, overshoot and IAE. Results from simulation show that even though tuning improves the performance of the PID controller, ANFIS-based approach provides better robustness and disturbance rejection performance.

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LIST OF ABBREVIATIONS

PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization
PSO-ACO	Hybrid Particle Swarm Optimization-Ant Colony Optimization
PID	Proportional-Integral-Derivative (Controller)
IAE	Integral of Absolute Error
ISE	Integral of Squared Error
ITAE	Integral of Time Absolute Error
Tr	Rise Time
Ts	Settling Time
Mp	Maximum Overshoot
Ess	Steady-State Error

LIST OF SYMBOLS

G_f	Transfer function of the flow process
A_f	Flow process gain
τ_f	Flow process time constant
T_f	Flow process delay
G_l	Transfer function of the level process
A_l	Level process gain
τ_l	Level process time constant
G_F	Flow sensor transfer function
A_F	Flow sensor gain
τ_F	Flow sensor time constant
G_L	Level sensor transfer function
A_L	Level sensor gain
τ_L	Level sensor time constant
G_r	ON/OFF controller transfer function
K_r	ON/OFF controller gain
G_{PID}	PID controller transfer function
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain
T_{inner}	Inner-loop (flow control) transfer function
T_{outer}	Outer-loop (level control) transfer function

CHAPTER 1

INTRODUCTION

1.1 Introduction

Regulation of flow rates has become an important task in many modern processes such as chemical plants, water purification facilities, oil/gas industries and heating, ventilation and air conditioning (HVAC) [1]. Flow rate regulation helps to maintain stability, ensure safety, increase energy efficiency, and produce products with required characteristics. Deviations in flow rate may affect processes, cause inefficiencies, and lead to potentially dangerous situations. One of the control strategies that became rather popular is Proportional-Integral-Derivative (PID) control. Its implementation is rather easy, while performance is relatively good across many applications. PID regulates the system by taking into account present, past, and anticipated errors. However, it is crucial to tune PID properly to achieve maximum performance. Proper tuning involves defining parameters such as K_p , K_i , and K_d . Several traditional control methods such as ZN or Cohen-Coon were widely used in practice to determine PID parameters. They are easy to use, but not suitable for nonlinear or complex systems. Traditional controllers tend to have high overshoot, long settling times and inability to cope with disturbances well. To address these problems, advanced optimization approaches have been applied. Metaheuristic optimization algorithms such as PSO and ACO have revealed excellent performance in solving nonlinear system problems. This paper proposes a hybrid of PSO and ACO approach to tune PID, which would allow PSO to find global minimum, while ACO would explore local space. Intelligent control technologies such as ANFIS are also becoming increasingly popular. By using combination of artificial neural networks along with fuzzy inference systems, ANFIS enables efficient adaptive behavior. ANFIS learns about process dynamics and can easily cope with uncertainty and disturbance issues. This thesis will consider a development and analysis of the hybrid ACO-PSO tuned PID control and ANFIS-based control as alternative flow rate regulating method. Comparative analysis of the two approaches will be provided [2].

1.2 Related Work

Control of flow rate is a topic that has received significant research in the past few years in the area of industrial automation systems and process control. Due to their linear system and good performance, the conventional PID controllers have been widely used for flow regulation. Numerous tuning techniques including Ziegler-Nichols and Cohen-Coon have been suggested to set PID parameters. But these techniques are not always successful in nonlinear systems and for disturbances.

Researchers have investigated tuning methods based on optimization to enhance PID tuning. Kennedy and Eberhart introduced a new optimization method called PSO which has been successfully used for tuning the parameters of the PID because of its ability to converge rapidly and to search globally. The performance of the PSO based PID controller has been shown to be superior in transient response, overshoot, and to attain a zero steady state error compared to conventional tuning.

Another approach, called ACO proposed by Dorigo, has also been used for many complex optimization problems. ACO offers pheromone search mechanisms that find optimal solutions, and has powerful local search ability. Some research has demonstrated that PID tuning in an ACO mode increases the stability of the system and increase the accuracy of the control.

More recent research has been related to hybrid PSO-ACO optimization methods in order to exploit the benefits of both algorithms. The hybrid ACO-PSO methods combine the exploration ability of PSO and the exploitation ability of ACO to achieve better convergence and better optimization performance [3].

Intelligent control techniques like ANFIS have been attracting great interest aside from optimization methods. ANFIS is a hybrid modelling technique that is the fusion of ANN and FLC for the modelling of nonlinear systems. It has been proved that the ANFIS based controllers have better disturbance rejection, adaptability and robustness as compared to conventional PID controller. The studies are motivation to develop hybrid optimization and intelligent control solutions for better flow rate regulation system.

1.2.1 Traditional Methods

Traditionally, control systems for maintaining the desired operating conditions in industrial processes have been used. The PID controller is one of the most frequently used of these methods because it has a simple control structure and it is easy to implement and perform well. PID controllers are widely used in flow rate control systems for regulating the flow rate of a process to a desired value, even in the presence of process variation and disturbances [4].

There are three control actions in the PID controller . The proportional action is to produce an output proportional to the current error, the integral action will remove steady state error and the integral will be the accumulation of all previous errors, and the derivative action will predict future trends in the error to help stabilize the system. By combining the two actions, the PID controller can produce a satisfactory control performance in many industrial applications. Several classical tuning methods have been developed to calculate the PID controller parameters: ZN, Cohen-Coon and hit trial and error methods. One of the most common methods, and gives parameter settings according to the characteristics of the system response, is the ZN method. Also, Cohen-Coon method enhances controller tuning for processes with time delay. Tuning approaches are simple and easy to implement, but have some drawbacks for nonlinear and dynamic systems. Such techniques suffer from large overshoot, long settling time, oscillatory response and poor

disturbance rejection [5]. However, in real industrial systems, flow processes could be nonlinear, parameters of the system may be uncertain, and external disturbances may be present, which reduces the effectiveness of the conventional PID methods.

To overcome these limitations, advanced optimization and intelligent control techniques have been studied to significantly enhance performance of the controller. The modern approaches offer increased adaptability, robustness and accuracy than the conventional control techniques, especially in complex industrial environments.

1.2.2 Metaheuristic Algorithms

With Metaheuristic algorithms are powerful optimisation techniques that can be applied to solve complex engineering problems which would otherwise be hard to tackle with simple mathematical tools. These algorithms are based on nature, biology and evolution. Metaheuristic (MH) algorithms are of immense interest in the field of control engineering for optimizing controller parameters, and enhancing system performance.

Metaheuristic methods are different from the classical optimization algorithms, in that they do not need detailed mathematical modelling and they are able to search large solution spaces efficiently. They are especially well suited for nonlinear, multi-variable and dynamic systems where classical solutions do not give optimal solutions. They are widely used algorithms for tuning the PID controller to reduce the performance indices like overshoot, settling time, rise time and steady state error [6]. One of the most commonly used metaheuristic algorithms which have inspired from the social behaviour of bird flocking along with fish schooling is PSO. The PSO algorithm works by taking particles through the search space and then modifying their position in case they are better than others or better than the original solution. PSO offers a rapid convergence and an excellent global search capability, useful for controller optimization.

Another important metaheuristic algorithm inspired by ants' food searching behavior is Ant Colony Optimization (ACO). Ants use pheromone trails, which are used to identify optimal paths. ACO has proven to be very effective in local search and solution refinement and has been used in optimization problems in control systems. Individual metaheuristic algorithms may have advantages in terms of performance, but they can also have disadvantages such as premature convergence or slow optimization speed. So, hybrid metaheuristic algorithms that fuse two or more algorithms were developed to improve the efficiency and accuracy of optimization. Metaheuristic algorithms have several advantages: robustness, adaptability, and can solve nonlinear systems. Because of these advantages they are a valuable aid for modern control system optimization and intelligent process automation.

1.3 Summary of Work

The current research study emphasizes on advanced control schemes for the efficient flow rate control for industrial process systems. The aim of the study is to enhance the performance of the traditional flow control method by incorporation of the hybrid optimization technique and intelligent control technique. During the first part of the task, an optimization of a PID controller is performed with the use of hybrid ACO and PSO algorithm. In this article, hybrid ACO-PSO method is presented, which is the combination of global search ability of PSO and local search ability of ACO to get optimal PID parameters. This optimized controller is optimized to minimize overshoot, settling time and provide overall stability of the system.

An intelligent data-driven controller for flow rate regulation based on ANFIS is designed in the second part. ANFIS controller integrates the learning ability of neural network with the reasoning ability of fuzzy logic to give a good response to the nonlinearity, uncertain factors and external disturbance in the industrial system. Modelling and simulation of the flow control system is done by means of appropriate software tools. The performance is evaluated based on standard performance parameters like the rise time, settling time, overshoot and IAE. The effectiveness of the three different types of controllers, conventional PID, hybrid ACO-PSO tuned PID, and ANFIS, is compared using the various operating conditions. Based on the results from the research, it can be concluded that the hybrid ACO-PSO tuned PID controller can significantly enhance the performance of the conventional PID controller. Moreover, the ANFIS controller shows enhanced adaptability, robustness and disturbance rejection performance, which makes it very appropriate for nonlinear industrial flow control applications.

1.4 Outline of Dissertation

The dissertation is structured into five chapters, each deal with a specific issue pertaining to the proposed research work on flow rate regulation using hybrid optimization and intelligent control techniques.

Chapter 1: Introduction

Chapter 1 is a general introduction on flow rate control systems and its importance in the field of industrial application and explains the need for efficient control strategies for flow rate control systems. It consists of the work related to it, traditional control methods, metaheuristic algorithms and summary of the same work, the objectives and scope of research.

Chapter 2: Methodology

The methodology that has been incorporated in the research work is described in this chapter. It gives the explanation of the working of PSO, ACO and hybrid algorithm ACO-PSO for tuning PID controller. The detail design and implementation of ANFIS controller are also explained in detail.

In Chapter 3, we explore how to model a system and design a controller.

In this chapter, the mathematical model of the flow rate control system is presented, and the conventional PID controller, the hybrid ACO-PSO tuned PID controller and the ANFIS controller are designed. The simulation setup and system parameters that are utilized for the analysis are also included.

Chapter 4: Results and Discussion

The chapter concludes by summarizing the findings and outlining the potential for the future.

The overall research findings and conclusions from the study are summarized in this chapter. It also outlines the benefits of the proposed techniques and offers ideas for future research that could enhance the performance of an intelligent flow control system.

1.5 Conclusion

In this chapter, a detailed description and overview of flow rate regulation systems were provided along with the significance of a successful control strategy in industry. The problems of conventional PID controller tuning techniques were discussed, especially when the system is nonlinear and there are other disturbances. To deal with these challenges, advanced optimization techniques and intelligent control methods were introduced [7].

The chapter also discussed the related work in the field of PID optimization and intelligent flow control systems. Efficient approaches for optimizing the parameters of the controller such as PSO and ACO were discussed in the context of metaheuristic algorithms. In addition, the importance of using intelligent methods like the ANFIS to deal with nonlinearity and uncertainty was introduced.

The proposal of the research work was presented, which includes the development of a hybrid ACO-PSO tuned PID controller and an ANFIS-based intelligent controller

for better flow rate control. Outline of the dissertation was also discussed to give an overview of the organisation of the research work [8].

The overall aim of this chapter was to set the groundwork and motivate the proposed work. The methodology, system modelling, controller design, simulation analysis and performance evaluation of the proposed control strategies are discussed in the following chapters.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

It is necessary to provide proper control of the flow rate in industrial process control systems. Controlling the flow rate correctly in various industries such as the chemical industry, power generation from oil and gas, water treatment facilities, and heating and cooling plants is essential. When controlling the flow rate correctly, we may expect the process stability, security, efficient energy consumption and high-quality product. Industrial control systems have a lot of features. Therefore, controlling the flow rate requires a lot of effort because industrial systems are complex and there are numerous elements that affect their performance.

For a long time, Proportional-Integral-Derivative controllers, which are known as PID controllers, have been successfully used to control the flow rate in the processes of the mentioned industries. They have proved to be reliable, easy to tune, and simple in implementation. The Ziegler-Nichols tuning method and the Cohen-Coon method for the design of PID controllers are widely used by engineers. The results achieved by means of these methods are acceptable in case of relatively uncomplicated control systems. In complex control systems, they can lead to serious consequences. Therefore, scientists developed special algorithms for the design of controllers. There are two types of algorithms: PSO and ACO [9]. PSO is effective when it comes to exploring solutions while ACO provides detailed search. Moreover, there is an algorithm for the design of controllers obtained by combining PSO and ACO. Recently, scientists have also paid attention to intelligent control. Intelligent controllers based on Adaptive Neuro-Fuzzy Inference Systems or ANFIS are used for managing complex control systems since they are adaptable. Also, these systems are very robust.

This chapter deals with research related to PID controllers, optimization algorithms (PSO, ACO), ANFIS controllers, and their application in practice. In particular, we will consider the use of these concepts to regulate the flow rate in systems. The topic of flow rate regulation systems is very important because the development of methods for the regulation of the flow rate is essential for us to achieve the desired results in our research work [10]. Flow rate regulation systems are applied in industry and should be optimized properly. Flow rate is controllable object.

2.2 Optimization Techniques

There has been growing interest in the application of optimization approaches to control engineering in recent years as a means of achieving better performance in industrial applications. In cases where optimization approaches are employed in flow rate control systems, the optimization approach can be used to obtain optimum values of control parameters that lead to higher stability, faster dynamic response, and lower control errors. Traditional approaches to optimizing controller parameter settings are often unsatisfactory, especially for nonlinear systems. Therefore, there has been a rising trend in the use of more advanced approaches.

An optimization problem refers to a problem of choosing from available options the option that gives the most desirable results within certain restrictions. In control engineering, the objective of optimization is to minimize parameters like the steady-state error, rise time, overshoot, settling time, and other undesirable system responses. Over the years, various optimization techniques have been formulated from mathematics, biology, and nature. One category of optimization techniques is called metaheuristic optimization and involves techniques such as Particle Swarm Optimization and Ant Colony Optimization. Metaheuristic algorithms are effective in solving optimization problems associated with nonlinear, multivariable, and complex functions without detailed knowledge of the system. The strength of metaheuristic algorithms is their capability to perform global searches without having to rely on complicated mathematical models. The Particle Swarm Optimization (PSO) technique is inspired by the nature of birds and fishes when they forage for food in groups. PSO has great capabilities for exploration and quick convergence to solutions.

On the other hand, Ant Colony Optimization (ACO) uses the concept of foraging behavior of ants which is characterized by pheromones. Ants communicate using pheromone trails and follow them in order to reach destinations as quickly as possible. The strength of Ant Colony Optimization is efficient local search capabilities and refinement of solutions.

Both PSO and ACO offer improved optimization results but each has its own weakness. Hybrid optimization algorithms incorporating PSO and ACO are thus formulated to benefit from their strengths.

2.2.1 Ant Colony Optimization (ACO)

Ant Colony Optimization is inspired by the food-searching behavior of ants. Ants communicate through pheromone trails to identify the shortest path between source

and destination. ACO provides efficient local search capability and improves solution refinement [9].

As a matter of fact, ants are known to release a chemical substance referred to as pheromones while moving on a certain path. Ants tend to move along paths that have high levels of pheromones since they attract them. As a result, the shortest path usually has the highest level of pheromones because it is traversed frequently by ants. In the same way, ants can identify the shortest path easily.

Artificial ants are initiated in the problem domain when using ACO algorithm. Each of the ants builds a solution that is based on the probabilistic selection of pheromone trails and heuristic information [29]. Once the search process is completed, the value of pheromones is updated depending on the quality of the solutions acquired. Better solutions get increased pheromone values and hence the chances of being selected in subsequent iterations increase.

The strengths of the ACO algorithm include strong local search ability, robustness, distributed computation, and adaptation to dynamic environments. These strengths make the use of ACO algorithm applicable in numerous engineering applications, including routing, scheduling, power systems, and controller parameter optimization.

In control engineering, the ACO algorithm is used extensively for optimizing the parameters of PID controllers in order to enhance the system performance. The algorithm manages to minimize system performance characteristics such as overshoot, settling time, and steady-state errors. Nevertheless, the ACO algorithm takes long to converge and is relatively slow in computation if used alone. Hybrid methods involving ACO and PSO algorithms are used to address these weaknesses [30].

ACO Algorithm Flowchart for PID Tuning

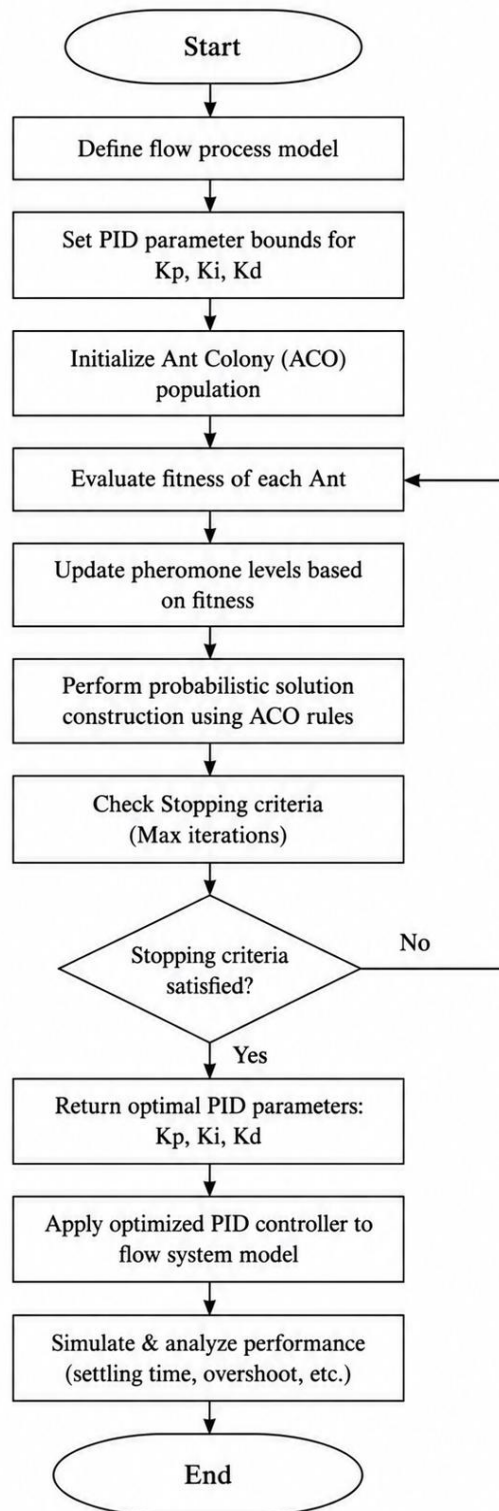


Figure 2.1: Flowchart of ACO Algorithm

2.2.2 Particle Swarm Optimization (PSO)

Partitions in PSO are the candidate solutions to that optimization problem. The motion of particles occurs based on their velocities and positions [35]. PSO consists of two important aspects – the personal best position of a particle (personal best or pbest), and the global best position of the particles (gbest). With the help of adjusting the position and velocities of particles, PSO approaches the optimal solution [30].

As can be seen from the velocity and position update formulae of PSO, exploration and exploitation of the algorithm are possible due to that. On the one hand, exploration is required for searching new zones of the solution space, whereas exploitation means finding the better values within the obtained solutions.

Some of the major pros of PSO include easy implementation, few parameters that are needed to control, quick convergence, and efficient exploring of the solution space. Such features made PSO very popular in various optimization problems related to power systems, robotics, artificial intelligence (such as tuning of neural networks), and others.

Tuning of the parameters of PID controllers in order to achieve better system performance is one of the major uses of PSO in control engineering. Performance measures that are being minimized by PSO include such factors as rise time, settling time, overshoot, and steady-state error. When compared to other methods of tuning, PSO gives better results[32].

Some of the drawbacks of PSO include its vulnerability to premature convergence and tendency to being trapped into local minima especially in nonlinear systems. To avoid these shortcomings, hybrid optimization algorithms that combine PSO with other algorithms such as ACO are suggested for PSO.

PSO Algorithm Flowchart for PID Tuning

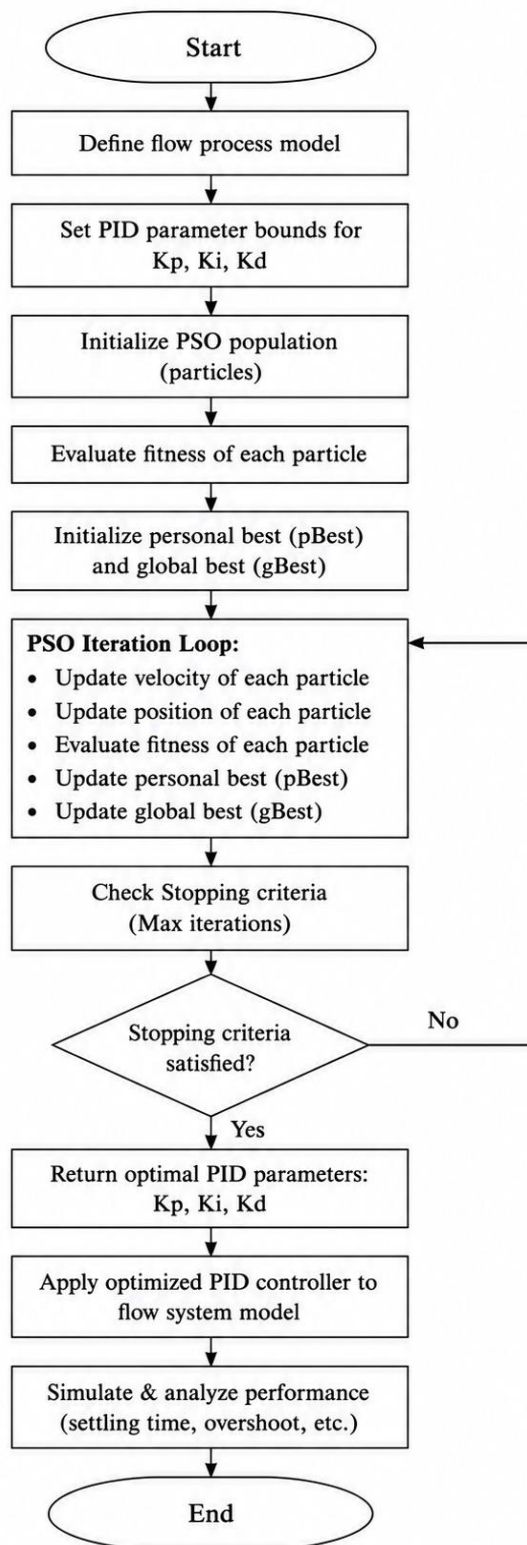


Figure 2.2: Flowchart of PSO Algorithm

2.2.3 Hybrid ACO-PSO Algorithm

Among several novel optimization approaches, hybrid ACO-PSO stands out because of its unique combination of capabilities provided by Ant Colony Optimization and Particle Swarm Optimization. The purpose of developing such a hybrid optimization technique is aimed at improving optimization performance through optimizing the performance of each technique involved in the process.

One of the features of Particle Swarm Optimization is its high global search ability, which allows the algorithm to search for near-optimal solutions quickly. However, one of the drawbacks of the algorithm is the possibility of premature convergence, especially in case of highly nonlinear systems [33].

On the other hand, Ant Colony Optimization possesses better solution refinement capabilities due to pheromone updating mechanisms, which increase search intensity for better results. On the other hand, ACO is less effective in terms of cost-efficiency and quick convergence [34].

Combining PSO and ACO provides an opportunity to improve optimization performance significantly by enhancing convergence, achieving accurate results, and increasing efficiency. Using PSO, it is possible to conduct the process of global search and identify near-optimal solutions. In turn, ACO may be used for the exploitation part of the process through the process of pheromone updating.

As far as application in control engineering is concerned, hybrid algorithms are widely used for tuning parameters of PID controllers like K_p , K_i , and K_d . Optimized parameters help reduce performance indicators like rise time, settling time, overshoot, and steady-state error.

Among the numerous advantages that can be attributed to the hybrid approach include fast convergence, high-quality solutions, small amount of optimization errors, and disturbances rejection ability. In particular, ACO-PSO hybrid algorithms were found to be rather efficient in nonlinear dynamic flow rate control systems.

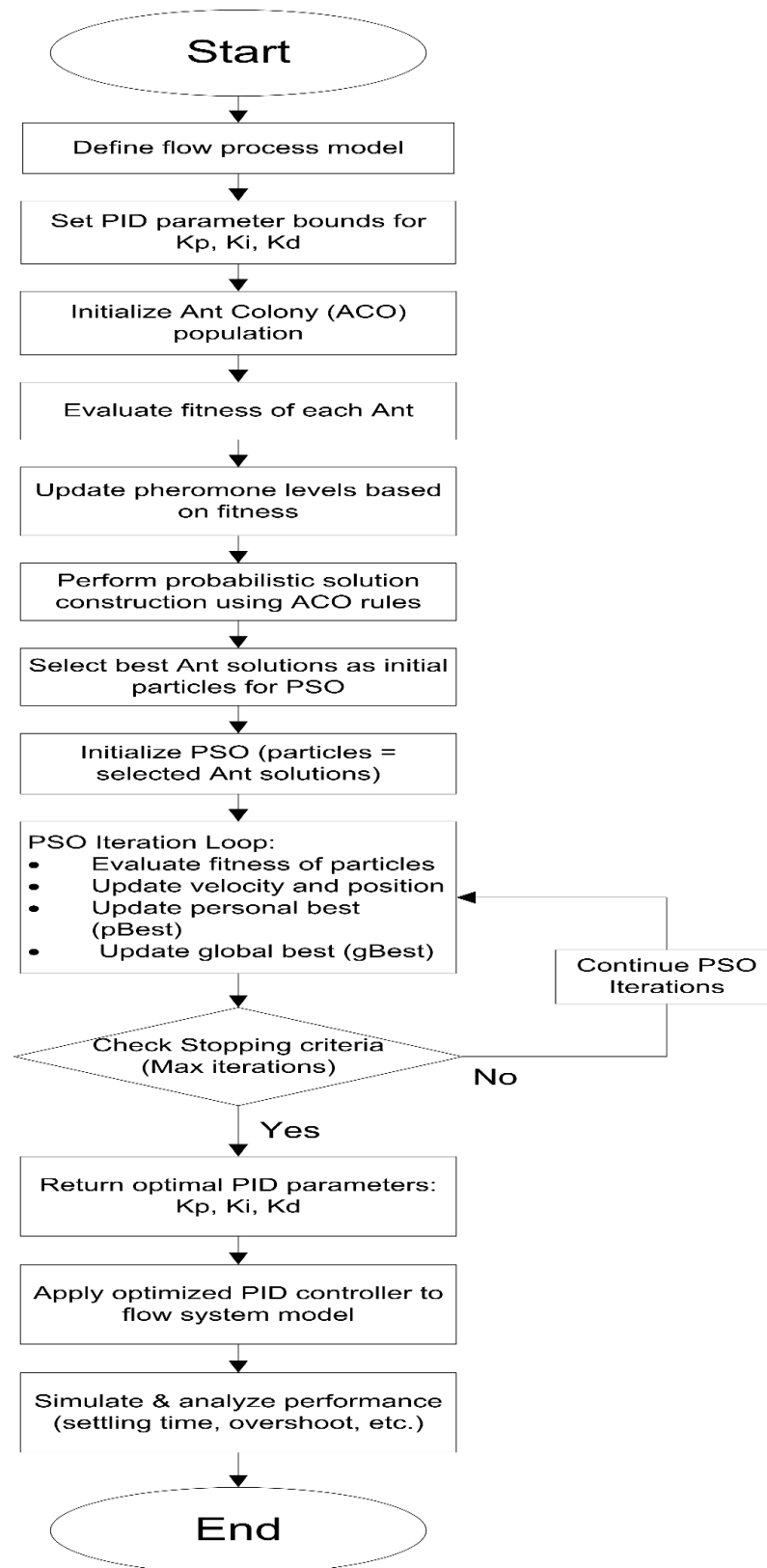


Figure 2.3: Flowchart of Hybrid ACO- PSO Algorithm

2.3 Performance Metrics

In order to analyze the performance of a controller and to direct the process of optimization, some of the most important time-domain performance measures are generally taken into consideration. These measures assist in defining the performance of the control system in terms of efficiency, effectiveness, and stability in meeting the output specifications. The principal measures are Rise Time (T_r), (T_s), (M_p), (E_{ss}), and IAE. Each of these, in combination, gives a complete view of system behavior and is crucial for validation that the control design satisfies performance requirements.

Rise Time (T_r) is the time taken for the system response to change from 10% to 90% of the final steady-state value.

Settling Time (T_s) is the time period in which the output of the system gets stabilized to a specified limit (normally within 2% or 5%) of the final value without oscillation beyond that limit.

Maximum Overshoot (M_p) is the amount by which the system response overshoots the desired final value, as a percentage of that value. Steady-State Error (ESS) is the difference in the output required and the output obtained when the system settles.

Steady-State Error (E_{ss}) measures the difference between the actual output and the desired output after the system has settled.

Considering all these matrices, it allows for a balanced controller design that emphasizes a fast response, minimal overshoot, stability, and robustness to disturbances. Optimization based on these performance metrics is essential for achieving high-performance control systems in practical applications.

While choosing cost function for minimization of the error, it is important to know which performance index will work best with the given system. Integral performance indices are crucial for objective evaluation of control system performance. Three popular indices are shown in Table 2.1.

Table 2.1: Difference between I.S.E, I.T.A.E, and I.A.E

Metric	Definition	Characteristics
ISE (Integral of Squared Error)	$ISE = \int_0^T e^2(t)dt$	Penalizes larger errors more heavily due to the squaring.
ITAE (Integral of Time-weighted Absolute Error)	$ITAE = \int_0^T t e(t) dt$	Penalizes errors that persist longer, encouraging faster settling.
IAE (Integral of Absolute Error)	$IAE = \int_0^T e(t) dt$	Measures the total absolute error over time.

In this study, IAE is selected because:

- IAE penalizes all errors equally, avoiding excessive sensitivity to large initial transients, as seen with ISE, or prolonged minor errors, as emphasized by ITAE. This characteristic ensures consistent control performance across a wide range of system operating conditions, making it best for real world nonlinear systems.
- IAE is computationally simple to implement, which is beneficial for real-time applications.
- IAE also promotes smoother control actions, avoiding the aggressive responses that might result from minimizing ISE, and preventing noise amplification.

In the event of a sudden disturbance, minimizing IAE leads to a steady correction of the error without overreacting. Unlike ISE, might cause excessive control effort, or ITAE, which could overly prioritize late-stage errors.

2.5 Conclusion

This chapter has given a comprehensive review of the literature on flow rate control systems, optimization, and intelligent control. The drawbacks associated with the use of conventional PID controllers and conventional tuning methods have been outlined, especially in dealing with non-linear systems and disturbance situations. In order to solve these problems, optimization techniques such as ACO and PSO have been adopted.

The concepts of working principle, advantages, and disadvantages of the ACO and PSO optimization algorithms have been explained. Additionally, a combination of both ACO and PSO optimization algorithms has been discussed in order to form a

more powerful hybrid optimization technique that integrates the strengths of both algorithms.

This chapter has also given an overview of the important performance criteria used for measuring controller performance, which includes rise time, settling time, overshoot, steady state error, and IAE . These performance criteria will be used for the comparative performance analysis between the conventional PID controllers, optimized PID controllers, and intelligent ANFIS based controllers [14].

From the above literature, it is evident that intelligent and optimization-based control techniques are superior to traditional ones with regard to adaptability, robustness, and disturbance rejection. Thus, the use of hybrid optimization and intelligent control techniques can lead to successful implementation of flow rate regulation systems.

The next chapter is devoted to the mathematical modeling of the flow rate control system, as well as the design of hybrid ACO-PSO based PID and ANFIS controllers. disturbances.

CHAPTER 3

SYSTEM DESCRIPTION

3.1 Introduction

Mathematical modeling and design of the controller play an important role in achieving an effective flow rate regulation system. The accurate mathematical modeling of the process aids in the analysis of its dynamics and facilitates the design of appropriate control strategies. The design of flow control systems in industry faces challenges because of the presence of nonlinearity, disturbances, and variations in the system parameters.

The ultimate goal of flow rate control systems is to regulate the flow to desired levels and minimize error in the system while maintaining stability. Industrial systems use PID controllers due to simplicity and reliability in operation. However, the performance of the PID controllers depends significantly on the appropriate tuning of the controller parameters. Otherwise, the system may face problems such as overshoot, oscillations, longer settling time, and disturbance rejection capacity.

In order to improve the performance of flow rate control systems, advanced optimization methods and intelligent control techniques are used in this study. In this case, hybrid ACO-PSO is applied to optimize the parameters of the PID controller. Hybrid optimization technique is a combination of the advantages of the PSO algorithm and ACO algorithm, which makes the optimization process more effective. Apart from optimization based control, an ANFIS controller is developed for intelligent control of the system. ANFIS controller uses the advance learning ability of neural networks and the great reasoning capability of fuzzy logic [15].

This chapter presents mathematical modeling of the flow rate control system and the design and implementation of conventional PID, hybrid ACO-PSO tuned PID, and ANFIS controllers. Problems [35].

3.2 System Design

The design of the proposed flow rate regulation system involves the process model, sensing unit, controller unit, actuator, and feedback system. In this case, the main objective of the proposed system will be the precise maintenance of the desired flow rate under variable operating conditions and disturbances.

The design of the controller entails a continuous feedback control system whereby the difference between the desired flow rate and actual flow rate at each instant in

time is obtained. This error is then used by the controller in generating the required control action.

The following are the three approaches used in the design of the controller for the proposed system:

- Conventional PID controller
- Hybrid ACO-PID tuned controller
- ANFIS-based intelligent controller

The conventional PID controller forms the basis of the control system design in the absence of more efficient controllers. In this approach, a controller is developed whose output signal is a function of the sum of proportional, integral, and derivative terms [28][29].

The performance of the PID controller depends on the parameters K_i , K_p , and K_d , which need to be fine-tuned properly to obtain good results.

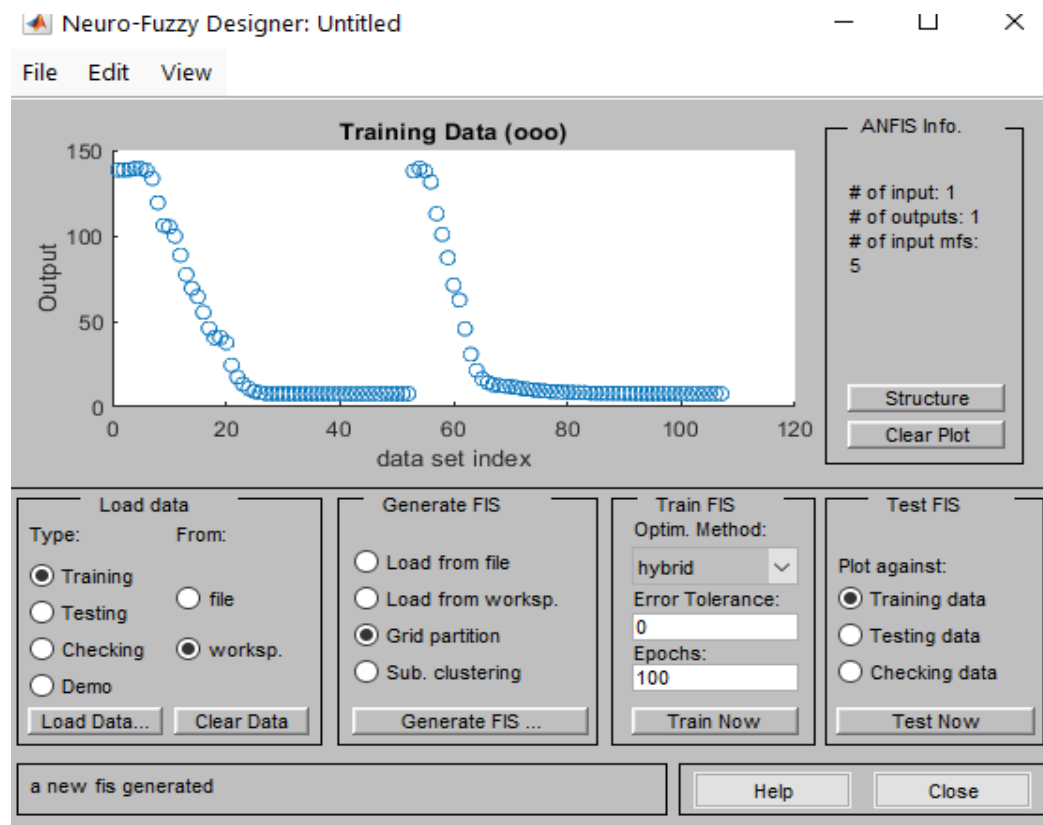


Fig 3.2. ANFIS Editor Tool Box

To achieve improved results, the hybrid ACO-PID tuned controller is developed using an optimization algorithm. The use of the hybrid ACO-PID controller will reduce performance indices such as overshoot, settling time, rise time, and steady-state errors

among others. Lastly, an adaptive neuro-fuzzy inference system (ANFIS) controller is designed for the proposed flow rate regulation system. The ANFIS controller utilizes training input-output data for learning and modeling of the process characteristics through fuzzy inference rules [16][17].

The use of this approach will result in intelligent control with effective disturbance rejection capabilities. The design of the above controller types has been achieved using the MATLAB/Simulink simulation software.

1. **ON-OFF Controller (G_r):**

The level error is first processed by an ON-OFF controller, represented by block **G_r** . This component provides a basic level of control, often used for switching actions such as enabling or disabling the main PID loop or providing an initial control action.

2. **PID Controller (G_s):**

The signal from the ON-OFF controller is then fed into the **PID controller (G_s)**. This controller calculates a continuous control signal based on **proportional (P)**, **integral (I)**, and **derivative (D)** terms, ensuring smoother and more accurate control compared to the ON-OFF method. The PID controller processes deviations and generates a flow rate setpoint to correct the error.

3. **Flow Process (G_f):**

The output of the PID controller acts as a command signal for the **flow process**, represented by **G_f** . This block simulates the dynamics of the fluid flow system such as the behavior of pumps, valves, and pipes-which directly affect the inflow to the tank.

4. **Disturbance Input:**

An external **disturbance** enters the system after the flow process block. This could represent environmental changes, valve position shifts, or pressure fluctuations. The disturbance impacts the final output and must be counteracted by the control loops.

5. **Level Process (G_l):**

The combined result of the flow input and disturbances is passed to the **level process block (G_l)**. This block models the tank level dynamics, where the flow influences the rise or fall of the liquid level. The output of this block is the **actual tank level**, which is the final controlled variable.

Feedback Mechanisms

To maintain control, the system incorporates two critical feedback loops:

- **Flow Sensor Feedback (G_f):**

A **flow sensor** measures the actual flow rate and provides feedback to the PID controller. This helps the controller compare the desired and actual flow rates, allowing for rapid correction of discrepancies.

- **Level Sensor Feedback (G_L):**

A **level sensor** measures the tank level and sends it back to the comparator at the input. This enables the continuous calculation of the level error and ensures that the system adjusts in real time to maintain the setpoint.

In summary, this cascade control block diagram shows how an **inner flow control loop** supports the **outer level control loop**, with the combination of sensors, controllers, and process models working together to achieve precise and stable regulation of a two-variable system. Figure 4 shows the block diagram of a cascaded flow-level control system.

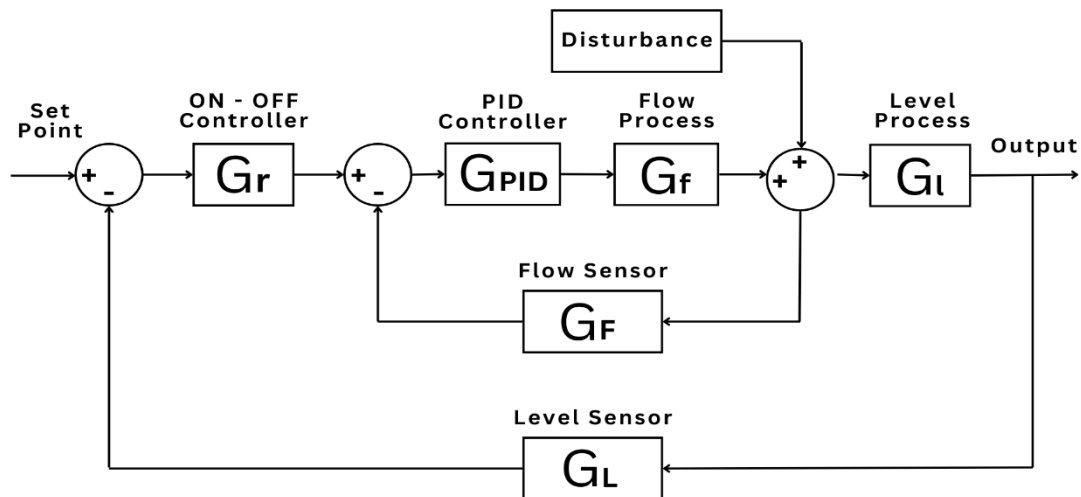


Figure 3.1: Block Diagram of Flow- Rate System

3.2.1 Flow Process Model

The flow process model explains the dynamic nature of the flow rate control system which is employed for industry purposes. In the case of the flow rate control system designed above, the flow process consists of the storage tank, pump, control valve, flow sensor, and pipeline configuration. The main goal of the proposed model is maintaining the flow rate at the desired level by controlling the flow process. Many factors affect the flow rate of the system like pressure difference, valve opening, physical properties of fluid, and characteristics of pipelines. Industrial flow process systems usually have nonlinearity and disturbance nature, which calls for the necessity of precise mathematical modeling of these systems.

The system used to control flow rate is modeled as a first-order dynamic process with time delay. Transfer function of the proposed flow process can be defined as follows:

$$G_f(s) = \frac{K_f}{\tau_f s + 1} \cdot e^{-t_f s} \quad (3.1)$$

where:

- K_f = Flow process gain
- τ_f = Flow process time constant
- t_f = Flow process delay

This transfer function specifies the relationship between the input variable and output variable. It is observed that the system's output variable is determined through the flow rate sensor and is compared to the desired value for generating an error term.

The obtained model is used for designing and implementation of both conventional PID control system and hybrid ACO-PSO tuned PID control systems as well as ANFIS control system [18][19].

3.2.2 Sensor and Actuator Description

Sensors and actuators play a crucial role in the development of the flow rate control system. They are important since they ensure that accurate measurement and control actions are achieved.

Flow Sensor

A flow sensor is employed to determine the actual flow rate of the fluid in the pipe. The sensor continuously measures the flow rate output from the process. It then converts the physical quantity into electrical signals that can be processed by the controller. The obtained value is then feedback into the controller to compare with the set value. The performance of the flow control system is highly influenced by the accuracy, response time, and reliability of the sensor. There are many types of flow sensors commonly applied in industries including turbine flow meters, electromagnetic flow meters, and ultrasonic flow meters among others.

Actuator and Control Valve

An actuator is tasked with the responsibility of controlling the system based on the controller output action. In the proposed system, the actuator will be used to open

or close the control valve based on the flow rate required. The control valve is the final controller element of the control system. It will help control the flow of fluid through adjustment to the valve position. The controller produces a signal based on the error existing between the setpoint and the measured value and sends it to the actuator.

3.2.3 Hardware Setup

The hardware arrangement employed for the flow rate control comprises the following equipment and components employed for monitoring, regulation, and flow rate control in the process. The hardware arrangement aims at simulating an industry-like environment for flow rate control to perform various measurements and control operations on the flow rate of the fluid.

The key components employed for the proposed setup are:

- Storage tank
- Centrifugal pump
- Control valve
- Flow sensor
- PID/ANFIS controller
- Data acquisition system
- Connecting pipelines

In the proposed hardware arrangement, the storage tank serves as the source where the fluid is stored. Then, the centrifugal pump will provide the required pressure for circulating the fluid in the pipeline system. On the other hand, the control valve is responsible for maintaining fluid in the process by means of regulating the quantity of fluid passing through the process. Moreover, a flow sensor will be fitted in the pipeline for measuring the actual flow rate of the fluid. The sensor will convert the physical flow rate to an electronic signal which is sent to the controller for further processing.

The measured flow rate will then be compared with the set point in order to generate the error signal. The controller then uses the error signal and executes the control algorithm to generate a particular signal for the control valve. The valve is then actuated to achieve the required flow rate. The data acquisition system will be employed in this project for conditioning signals, monitoring, and recording system parameters while performing the process. Finally, the MATLAB/Simulink software will be employed for performing all the simulations and control actions.

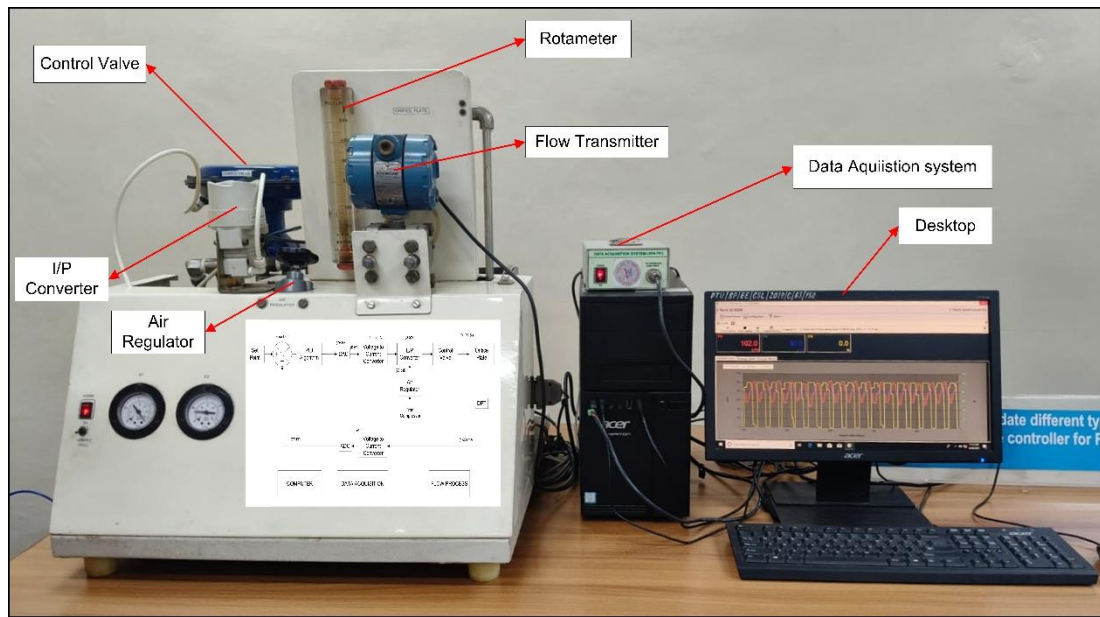


Figure 3.2: Experimental Setup of Hardware System

3.2.4 Mathematical Modeling

Mathematical modeling of the control system plays a vital role in its design and analysis. This is due to the fact that it gives a mathematical description of the dynamic nature of the flow rate control system and allows understanding the relationship between input and output signals. Precise modeling of the system is required to design efficient controllers and analyze system performance.

It can be noted from the proposed flow rate control system that the process is considered as a first order dynamic process. The flow rate of the system depends on various factors including the pressure of the fluid, valve position and pipe resistance. The controller controls the process by moving the control valve depending upon the error generated.

1. Flow Sensor Transfer Function (G_F):

The Flow Sensor's transfer function is modeled as a first-order system with a gain A_F and a time constant τ_F . It is expressed as:

$$G_F(s) = \frac{A_F}{\tau_F s + 1} \quad (3.2)$$

2. Level Sensor Transfer Function (G_L):

The Level Sensor's transfer function is modeled as a first-order system with a gain A_L and a time constant τ_L . It is expressed as:

$$G_L(s) = \frac{A_L}{\tau_L s + 1} \quad (3.3)$$

3. ON/OFF Controller Transfer Function (G_r):

ON/OFF controller representing the controller's gain with $u(t)$ representing step function showing switching behavior. It is expressed as:

$$G_r(s) = K_r * u(t) \quad (3.4)$$

4. PID Controller Transfer Function:

The PID controller's equation is expressed as:

$$G_{PID} = K_p + \frac{K_i}{s} + K_d s \quad (3.5)$$

Hybrid ACO-PSO algorithm is employed to optimize the obtained PID control parameters in order to improve the performance of the system. Also, ANFIS controller models the non-linear characteristics of the system using input and output training dataset and fuzzy inference rule base. The designed mathematical model of the flow rate control system is implemented using MATLAB/Simulink.

3.3 System Dynamics

1. Inner-Loop (Flow Control) Transfer Function (T_{inner}):

The inner flow control loop is the product of the PID controller and the flow process with flow sensor in negative feedback to both of them. This is expressed as:

$$T_{inner} = \frac{G_{pid} * G_f}{1 + G_F * G_{pid} * G_f} \quad (3.6)$$

2. Outer-Loop (Level Control) Transfer Function:

The disturbance transfer function G_d is summed up with the open-loop system G_{open} . The closed-loop transfer function is computed by taking the feedback of the open-loop system and disturbance and it is expressed as:

$$T_{outer} = \frac{G_r * T_{inner} * G_l}{1 + G_r * T_{inner} * G_l * G_L} \quad (3.7)$$

As the process's time constant is generally very high as compared to sensor's time constant ($\tau_{sensor} \ll \tau_{process}$). Therefore, $G_F = G_L = 1$ is reasonable for most systems because sensors are faster than processes. Now, Equation 3.6 and 3.7 can be expressed respectively as:

$$T_{inner} = \frac{G_{pid} * G_f}{1 + G_{pid} * G_f} \quad (3.8)$$

$$T_{outer} = \frac{G_r * T_{inner} * G_l}{1 + G_r * T_{inner} * G_l} \quad (3.9)$$

Table 3.1 summarizes the value of parameters used in the real system. The overall system becomes a cascade of two feedback loops, enabling faster correction of disturbances.

Table 3.1: Parameter Values of Flow-Level Control System

S. No.	Description	Parameter	Value(units)
1	Flow Process Gain	A_f	50
2	Flow Process Time Delay	t_f	1 second
3	Flow Process Time Constant	τ_f	30 seconds
4	Level Process Gain	A_l	0.13
5	Level Process Time Constant	τ_l	3 seconds
6	On/Off Controller Gain	K_r	5

3.4 Optimization Algorithm Parameters

Three optimization strategies were implemented to tune the PID controllers:

- Ant Colony Optimization
- Particle Swarm Optimization
- Hybrid ACO-PSO Algorithm

The parameters for each algorithm were carefully selected based on trial-and-error and literature review. Table 3.2 and Table 3.3 summarize the value of parameters used in the Ant Colony optimization Code & Particle swarm Optimizer respectively [20].

Table 3.2: Parameter Values of A.C.O Algorithm

S.No.	Parameter	Value
1	Number of ants (n_ants)	20
2	Maximum Number of Iterations	50
3	Pheromone importance factor (alpha)	1
4	Heuristic importance factor (beta)	5
5	Pheromone evaporation rate (rho)	0.5
6	Constant used for pheromone update(Q)	1
7	Initial Pheromone Levels, initialized to 1 for each ant and dimension(tau)	Ones (n_ants, dim)
8	Lower Bounds For PID gains [Kp,Ki, Kd](lb)	[0 0 0]
9	Upper Bounds For PID gains [Kp,Ki,Kd](ub)	[10 10 10]
10	Number Of Dimensions (Parameter to optimize: Kp, Ki, Kd)(dim	3

Table 3.3: Parameter Values of P.S.O Algorithm

S.No.	Parameter	Value
1	n_particales	30
2	Maximum Number of Iterations	100
3	Inertia weight (w)	0.7
4	Cognitive Coefficient (c1)	1.5
5	Social Coefficient(c2)	1.5
6	Lower Bounds For PID gains [Kp,Ki, Kd](lb)	[0 0 0]
7	Upper Bounds For PID gains [Kp,Ki,Kd](ub)	[10 10 10]

S.No.	Parameter	Value
8	Number Of Dimensions (Parameter to optimize: Kp, Ki, Kd)(dim)	3

3.5 Conclusion

This chapter presented a detailed summary of the cascade control system designed to regulate the liquid level and flow in a process tank using a master-slave PID control structure. The inner loop focused on controlling the flow rate, while the outer loop managed the tank level. Mathematical modeling of each component was discussed through first-order transfer functions, capturing the system's dynamic behavior accurately. Optimization algorithms, including ACO and PSO, were introduced to fine-tune the PID parameters for the flow control of the cascaded system. These algorithms were implemented in MATLAB, enabling precise controller tuning for improved system stability and accuracy.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the simulation results and analysis for the flow rate control system using different controllers have been presented. The aim of this chapter is to analyze the performances of the conventional PID controller, hybrid ACO-PSO based PID controller, and ANFIS based intelligent controller.

The simulations have been done using MATLAB/Simulink environment where the dynamics of the flow rate system have been studied and the different controllers have been implemented. Parameters such as rise time, settling time, overshoot, steady state error, and integral absolute error have been used as the performance indicators.

From the simulation results, one can understand the benefits that are offered by the hybrid optimization technique and intelligent control methods compared to the conventional PID controller. Comparative analysis helps us in understanding how much improvement has taken place through the proposed methods in terms of system stability, response time, and disturbance rejection capabilities.

4.2 Simulation Setup

In order to validate the effectiveness of the design technique used, a simulation model in MATLAB/Simulink was constructed and implemented. The simulation model was then employed to perform analysis and comparison of performance of PID controller, hybrid ACO-PSO tuned PID controller and ANFIS based intelligent controller under varied conditions.

The simulation setup includes the following:

•Flow Control System

The flow rate control process is simulated using a first order transfer function model that mimics the dynamics of the industrial flow rate control process.

•PID Controller

A PID controller is incorporated in the process control loop to ensure accurate regulation of the flow process through minimization of error between set point value and actual output.

•Hybrid ACO-PSO Tuned PID Controller

Parameters of the PID controller ((K_p , K_i , K_d)) are optimized using a hybrid ACO-PSO optimization algorithm for improved performance.

•ANFIS Based Intelligent Controller

Input/output training data is fed into the system along with fuzzy inference rules to construct ANFIS controller to regulate the flow rate intelligently.

•Disturbance Conditions

External disturbances are injected in the system to evaluate disturbance rejection capability of the controllers.

•Performance Analysis

The simulation environment created an effective framework to evaluate the efficiency and robustness of the design strategies implemented for industrial processes.

Software Tools: MATLAB R2024b (Simulink)

4.3 Performance Analysis

A simulation study of the flow rate control system was carried out using three control strategies: Conventional PID controller, Hybrid ACO-PSO tuned PID controller, and ANFIS intelligent controller. Performance measures that were used in evaluating the behavior of the control systems include rise time, settling time, maximum overshoot, and IAE [22].

In this case, an optimization algorithm called ACO-PSO was employed in optimizing the parameters of the PID controller for better performance. ANFIS intelligent control strategy is a technique that is adaptive and intelligent in nature for use in handling nonlinearities and disturbances [21].

Table 4.1 summarizes the performance comparison of conventional PID controller, Hybrid ACO-PSO PID controller, and ANFIS intelligent controller. Table 4.1

results have been obtained using the unit step response analysis of MATLAB/Simulink.

Table 4.1: Performance Analysis of A.C.O, P.S.O, Hybrid A.C.O-P.S.O and ANFIS

S.No.	Parameter	Conventional PID	A. C. O	P. S. O	A.C.O - P. S. O	ANFIS
1	Rise Time (s)	1.85	1.29	1.4	1.98	0.000566
2	Settling Time (s)	7.42	7.07	6.58	4.06	0.00339
3	Maximum Overshoot	1.18	1.14	1.07	1.01	0.505
4	Best Function $f(x)$	-	1.903	1.865	0.813	-

4.4 Hybrid ACO-PSO PID Controller Results

The Hybrid ACO-PSO tuned PID controller demonstrated significant improvement in flow rate regulation compared to the conventional PID controller. The optimized controller achieved reduced rise time, settling time, overshoot, and steady-state error. By combining the global search capability of PSO with the local refinement ability of ACO, optimal PID parameters were obtained efficiently. The system exhibited faster response, improved stability, and better disturbance rejection performance [23]. The simulation results confirm that the Hybrid ACO-PSO approach enhances controller effectiveness and provides reliable flow control under varying operating conditions.

Figure 4.1, 4.2, and 4.3, 4.4 shows the system response with optimized PID gains using A.C.O, P.S.O, and hybrid A.C.O-P.S.O respectively.

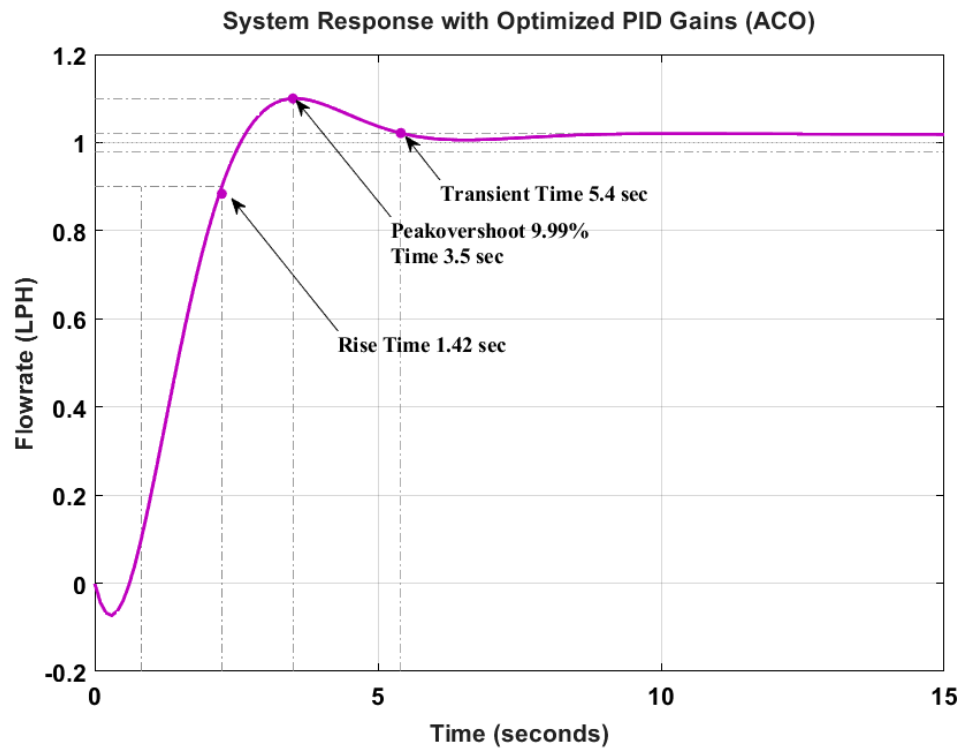


Figure 4.1: System Response with Optimized PID Gains using A.C.O

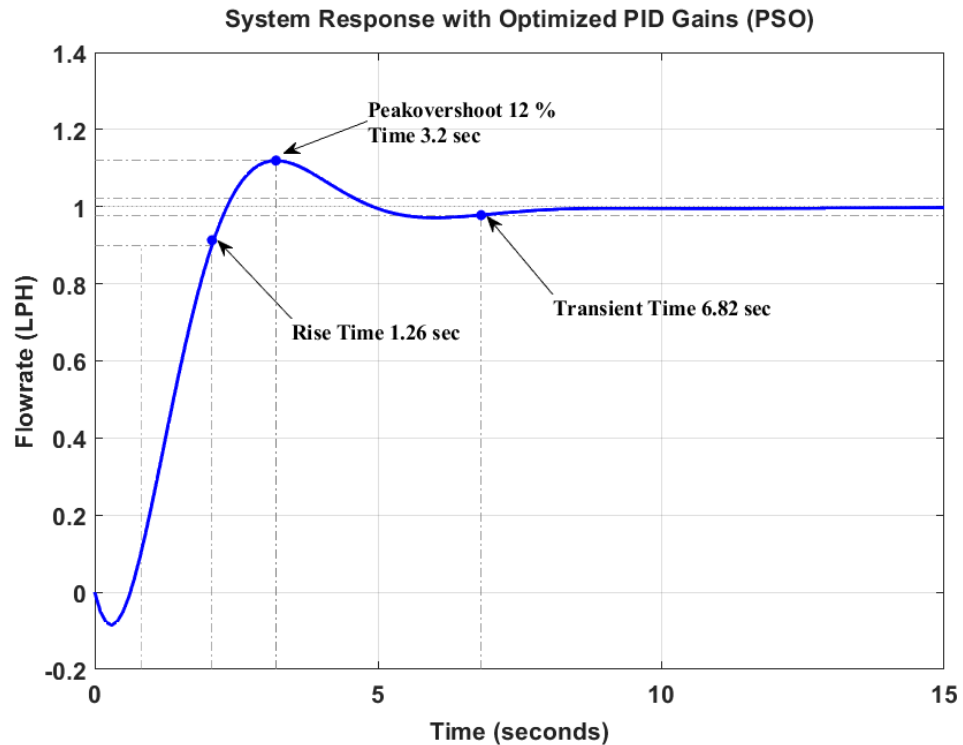


Figure 4.2: System Response with Optimized PID Gains using P.S.O

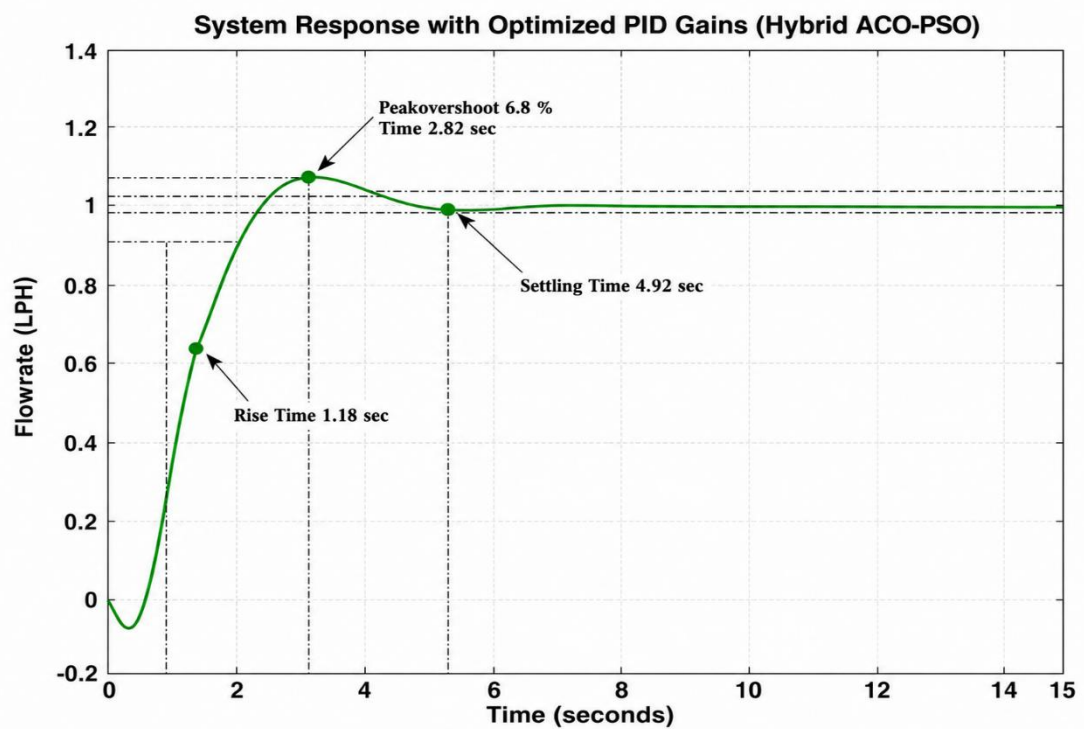


Figure 4.3 System Response with Optimized PID Hybrid ACO-PSO

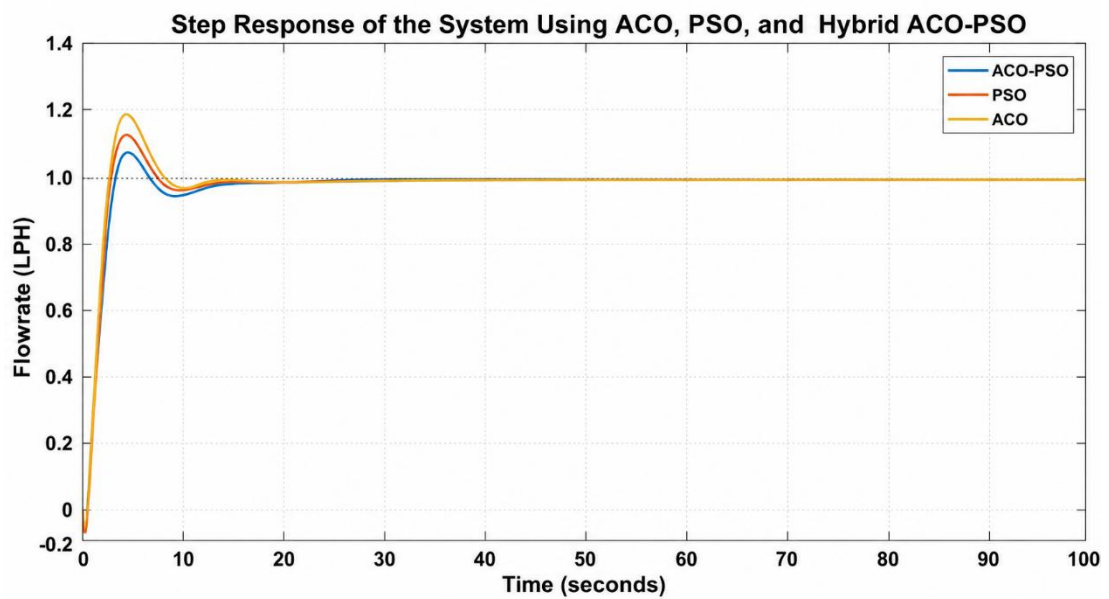


Figure 4.4: System Response with Optimized PID Gains using Hybrid A.C.O - P.S.O

4.5 ANFIS Controller Results

ANFIS controller provided superior performance in flow rate regulation due to its adaptive learning and nonlinear modeling capabilities. The controller effectively tracked the desired setpoint with minimal overshoot and very low steady-state error. It showed excellent robustness against disturbances and process variations, maintaining stable operation under dynamic conditions. Compared to both conventional PID and Hybrid ACO-PSO tuned PID controllers, ANFIS achieved faster settling, smoother response, and improved control accuracy [24]. The simulation results demonstrate that ANFIS is a highly effective intelligent control technique for industrial flow rate control applications.

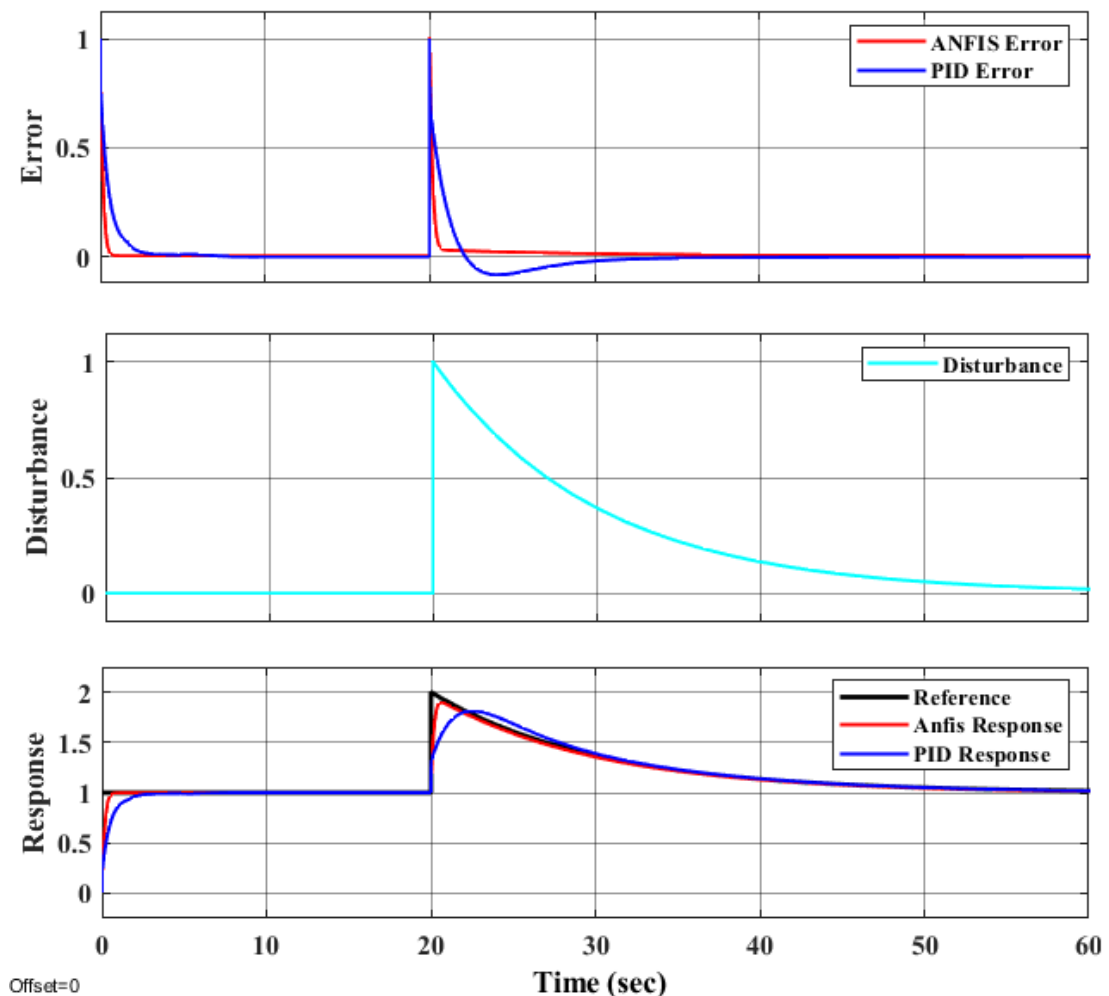


Figure 4.5: Comparison of System Response with Optimized PID and ANFIS

4.4 Disturbance Handling

Disturbance rejection capability is critical in ensuring stability and consistency in performance of flow rate control systems in industrial settings. Disturbances in

real life situations often result into deviations in the flow rate from its desired set point. In order to ensure that there is no disturbance from the desired operating point, a strong controller is needed.

In this study, disturbance in the system was done by introducing an external disturbance in the system at time $t = 50$ seconds while in operation. As a result of the disturbance, deviation was observed in the output of the process. The system responses with respect to Conventional PID, Hybrid ACO-PSO tuned PID, and ANFIS controllers were studied.

A remarkable reduction in the effects of the disturbance in the system by using hybrid ACO-PSO tuned PID controller was noted where oscillations were minimized in addition to the restoration of the flow back to the desired value. This is achieved through an optimization approach which is based on balancing the use of two algorithms namely the PSO, and ACO). In addition, a greater disturbance rejection capacity was realized using the ANFIS controller [25][26]. This controller was able to adjust itself rapidly and accurately according to changes in the process operating conditions and gave an almost zero steady state error.

The results have revealed a significant improvement in disturbance rejection in the case of Hybrid ACO-PSO tuned PID controller and ANFIS controller.

Figure 4.6 shows the output results after introducing delay disturbance in the system at $t = 50$ seconds. $t = 50$ seconds.

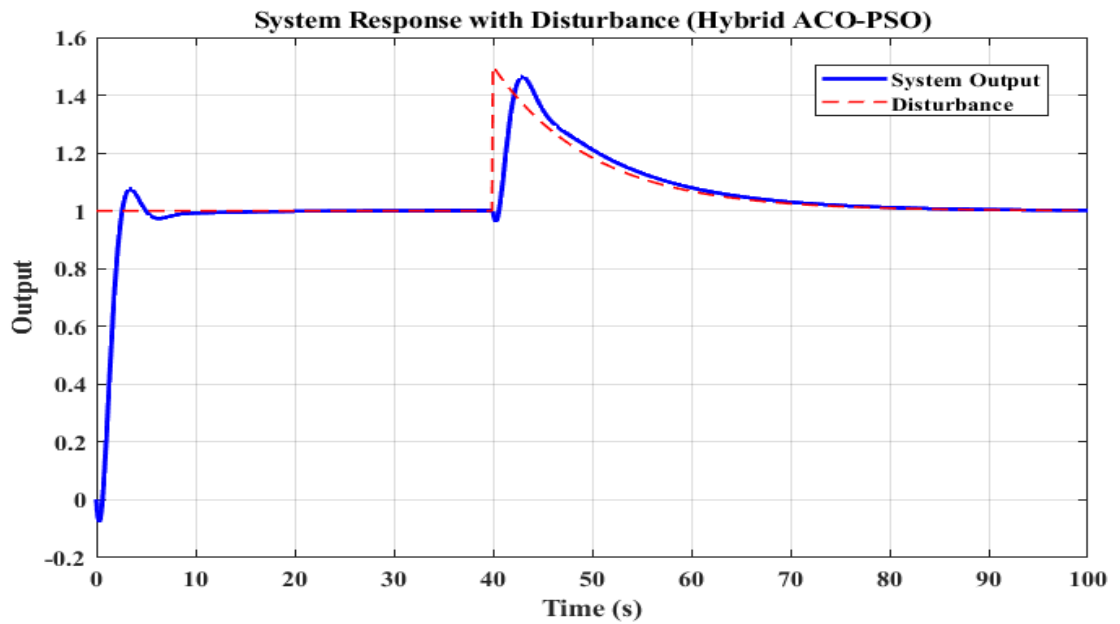


Figure 4.6: System Response with Delayed Disturbance at $t = 50$ seconds

PID controller effectively suppresses the disturbance's impact by damping of oscillations and returning the response to desired set-point ensuring robust system performance under dynamic conditions.

4.5 Optimized PID Parameters

The final optimized PID gains for the Hybrid ACO-PSO tuned controller were:

- $K_p = 2.2829$
- $K_i = 6.7975$
- $K_d = 0.6830$

These gains provided optimal performance in both steady-state accuracy and transient response.

4.6 Hardware Output Analysis

The validation through implementation is a significant stage in the realization of the efficiency of the designed control system. The hardware setup designed in this project comprises of a water tank, pump, control valve, flow sensor, controller, and monitoring interface. The system aims at ensuring that the process achieves the required flow rate.

For the designed system:

- The Flow Process forms the primary process in control systems whose purpose is to provide the required fluid flow within the pipeline.
- The Flow Sensor will measure the fluid flow rate in real time.
- The Hybrid ACO-PSO PID Controller generates the control signal for the system.
- The Control Valve and the Pump comprise of the final control elements in the process.

The hardware system is interfaced with the Human Machine Interface (HMI) that is developed with MATLAB software. Figure 4.6 below presents the hardware system response for the Hybrid ACO-PSO based PID controller through HMI interface.

Some of the major information presented in the interface includes:

- **SP (Set point):** The desired flow rate value chosen by the user.
- **MV (Measuring Value):** Flow rate measured in real time using the sensor.
- **PID Parameters:** The optimized proportional, integral, and differential gain values generated by the hybrid algorithm.
- **Real Time Response Graph:** This graph depicts the response of the system.

The response in the graph shown in figure above highlights how the system responds when the setpoint is changed and when any other disturbance occurs. The response shows that the optimized system performs effectively in regulation and stability of the process. Any deviation in flow that may be caused by external disturbance is easily attenuated for the system to achieve the desired operating point.

The error displayed on the graph can also be used as a parameter of monitoring the performance of the control system. Lower error value indicates effective flow rate regulation.

Also, the Process Flow Diagram on the HMI shows the information relating to:

- Operating status of pump
- Control valve operating status
- Direction of fluid flow through the pipeline
- Current status of the process

This graphical presentation facilitates effective visualization and easy user interaction and monitoring.



Figure 4.7: Hardware System Response of Hybrid ACO-PSO Tuned PID Controller

Hardware System Output

- **Stable Flow Rate Regulator:** The system provides stable fluid flow with minimal oscillations.
- **Good Disturbance Attenuation:** The response of the system recovers quickly when any external disturbance occurs.
- **Minimum Overshoot:** Any excess flow that may be caused by transient disturbance is prevented.
- **Optimum Stability:** The system runs smoothly under different process conditions.
- **Excellent Set point Tracking:** The controller tracks the set point very effectively with very minimum steady-state error.

4.7 Conclusion

Simulation and hardware-based performances of the designed flow rate control system have been analyzed using the proposed Conventional PID, Hybrid ACO-PSO tuned PID, and ANFIS controllers in this chapter. According to the outcomes obtained through MATLAB/Simulink simulations, the hybrid tuning technique has effectively enhanced the performance of the conventional PID controller by reducing the rise time, settling time, overshoot, and steady-state errors. In addition, the analysis based on disturbance revealed that the tuned controller can respond better compared with the other controller designs because of its fast recovery and stability capabilities. The ANFIS controller proved to be more adaptive because of its intelligent learning features. The practical performances of the proposed control system have been verified via hardware implementation, which also revealed precise setpoint tracking performance. problems.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

In the current research project, efforts were made to enhance the flow rate regulation through optimization and intelligence-based control techniques. Three types of flow controllers including conventional PID controller, optimized hybrid ACO-PSO tuned PID controller, and an intelligent ANFIS-based flow controller were developed and analyzed to evaluate their performance in detail.

The conventional PID flow rate regulator exhibited average control performance by showing higher overshoot, settling time, and less resistance towards external disturbances. In order to improve upon the basic performance of the PID flow rate controller, a hybrid ACO-PSO algorithm was introduced for the optimal tuning of the PID parameters. Hybrid optimization resulted in increased system stability, less overshoot, minimal steady state error, and better dynamics.

An intelligent ANFIS-based flow rate controller was also designed to manage the nonlinear behavior and uncertainties in the flow system. The ANFIS-based flow controller showed superior adaptability, disturbance rejection capability, and robustness than the other two conventional and optimized control systems.

MATLAB Simulink simulation results clearly showed the effectiveness of both hybrid ACO-PSO tuned PID flow controller and ANFIS controller.

Thus, it can be concluded that optimization and intelligence-based approaches offer effective control strategies for flow rate regulation systems.

5.2 Future Scope

However, despite the significant improvement in the flow rate control performance achieved using the proposed hybrid ACO-PSO tuned PID control strategy and intelligent ANFIS-based controller, there are some directions that should be considered for future research as follows:

- **Practical Real-Time Implementation of the Controllers Using Industrial Hardware:**

The suggested controllers can be implemented by using any real-time industrial hardware platforms, such as Arduino, Raspberry Pi, DSP processors, or even PLC-based systems for practical industrial applications.

- **Application to Other Non-linear Processors:**

The suggested control algorithm can be extended and used in other nonlinear industrial process controllers such as pressure control systems, temperature control systems, and level control systems.

- **Improvement in Intelligent Controller Design Using Artificial Intelligence and Machine Learning Techniques:**

Another potential research direction is using advanced machine learning and artificial intelligence techniques in addition to ANFIS in order to improve the adaptive learning capabilities and increase the prediction accuracy.

- **Integration of Proposed System in IoT-Based Industrial Automation:**

The proposed system can be used in industrial automation based on Internet of Things (IoT) technology.

- **Enhancing Disturbance Rejection Capability and Fault-Tolerance:**

Another interesting area of research is developing a technique for improving disturbance rejection capabilities and fault tolerance.

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APPENDIX I

MATLAB codes for different algorithms as explained in section 3.4 are as follows:

1. Ant Colony Optimization Code:

```
clc; clear; close all;

%% Parameters
Af = 50; tau_f = 30; td_f = 1; % Flow process
Al = 0.13; tau_l = 3; % Liquid process
Ad = 1; tau_d = 10; % Disturbance
Gr = 5; % ON/OFF controller
s = tf('s'); % Laplace variable

%% Transfer Functions

Gv = Al / (tau_l * s + 1);
Gp_delay = (Af * (1 - 0.5 * s)) / ((tau_f * s + 1) * (0.5 * s + 1));
Gd = Ad / (tau_d * s + 1);
plant_combined = Gv * Gp_delay;

%% ACO Parameters

n_ants = 20;
max_iter = 50;
alpha = 1; % pheromone importance
beta = 5; % heuristic importance
rho = 0.5; % evaporation rate
Q = 1; % constant for pheromone update

lb = [0 0 0]; % Lower bounds for Kp, Ki, Kd
ub = [10 10 10]; % Upper bounds

dim = length(lb); % Dimensions = 3 (Kp, Ki, Kd)
tau = ones(n_ants, dim); % Pheromone matrix
```

```

best_cost = inf;
best_sol = [];

%% Main ACO Loop

for iter = 1:max_iter
    solutions = zeros(n_ants, dim);
    costs = zeros(n_ants, 1);
    for k = 1:n_ants
        for d = 1:dim
            r = rand();
            solutions(k,d) = lb(d) + (ub(d)-lb(d)) * r; % Random selection
        end
        costs(k) = PID_Performance_Modified(solutions(k,:), plant_combined, Gd);

        % Update global best

        if costs(k) < best_cost

            best_cost = costs(k);

            best_sol = solutions(k,:);
        end
    end

    % Pheromone update

    for d = 1:dim

        tau(:,d) = (1 - rho) * tau(:,d);

        for k = 1:n_ants

            tau(k,d) = tau(k,d) + Q / costs(k);

        end
    end

```

```

end

fprintf('Iteration %d, Best Cost = %.4f\n', iter, best_cost);

end

%% Display Optimized PID

disp('Optimized PID Gains from ACO:');

disp(['Kp = ', num2str(best_sol(1))]);

disp(['Ki = ', num2str(best_sol(2))]);

disp(['Kd = ', num2str(best_sol(3))]);

%% Evaluate System with Optimized PID

Kp_opt = best_sol(1);

Ki_opt = best_sol(2);

Kd_opt = best_sol(3);

PID = Kp_opt + Ki_opt / s + Kd_opt * s;

closedLoop = feedback(PID * plant_combined + Gd, 1);

t = 0:0.1:100;

step(closedLoop, t);

title('System Response with Optimized PID Gains (ACO)');

xlabel('Time (s)');

ylabel('Output');

grid on;

%% Objective Function

function cost = PID_Performance_Modified(pid_params, plant, Gd)

    Kp = pid_params(1);

```

```

Ki = pid_params(2);
Kd = pid_params(3);
PID = Kp + Ki / tf('s') + Kd * tf('s');
T_cl = feedback(PID * plant + Gd, 1);

t = 0:0.1:100;
[y, ~] = step(T_cl, t);
error = abs(y - 1);
IAE = trapz(t, error);
cost = IAE;
end

```

2. Partical Swarm Optimization Code:

```

clc;
clear;
close all;

%% System Parameters

Af = 50; tau_f = 30; td_f = 1; % Flow process
Al = 0.13; tau_l = 3; % Liquid process
Ad = 1; tau_d = 10; % Disturbance
Gr = 5; % ON/OFF controller
s = tf('s'); % Laplace variable

```

%% Transfer Functions

$$G_v = A_l / (\tau_l * s + 1);$$

$$G_{p_delay} = (A_f * (1 - 0.5 * s)) / ((\tau_f * s + 1) * (0.5 * s + 1));$$

$$G_d = A_d / (\tau_d * s + 1);$$

$$\text{plant_combined} = G_v * G_{p_delay};$$

%% PSO Parameters

$$n_particles = 30;$$

$$\text{max_iter} = 100;$$

$$w = 0.7; \quad \% \text{ Inertia weight}$$

$$c1 = 1.5; \quad \% \text{ Cognitive parameter}$$

$$c2 = 1.5; \quad \% \text{ Social parameter}$$

$$lb = [0 \ 0 \ 0];$$

$$ub = [10 \ 10 \ 10];$$

$$\text{dim} = \text{length}(lb);$$

% Initialize particle positions and velocities

$$X = \text{rand}(n_particles, \text{dim}) .* (ub - lb) + lb; \quad \% \text{ Positions}$$

$$V = \text{zeros}(n_particles, \text{dim}); \quad \% \text{ Velocities}$$

% Personal and global bests

$$pbest = X;$$

$$pbest_cost = \text{inf}(n_particles, 1);$$

$$[gbest_cost, \text{idx}] = \text{min}(pbest_cost);$$

$$gbest = X(\text{idx}, :);$$

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```
%% Main PSO Loop
```

```
for iter = 1:max_iter
```

```
    for i = 1:n_particles
```

```
        cost = PID_Performance_Modified(X(i,:), plant_combined, Gd);
```

```
        if cost < pbest_cost(i)
```

```
            pbest_cost(i) = cost;
```

```
            pbest(i,:) = X(i,:);
```

```
        end
```

```
        if cost < gbest_cost
```

```
            gbest_cost = cost;
```

```
            gbest = X(i,:);
```

```
        end
```

```
    end
```

```
    for i = 1:n_particles
```

```
        r1 = rand(1, dim);
```

```
        r2 = rand(1, dim);
```

```
        fprintf('Iteration %d: Best Cost = %.4f\n', iter, gbest_cost);
```

```
    end
```

```
%% Display Optimized PID
```

```
disp('Optimized PID Gains from PSO:');
```

```
disp(['Kp = ', num2str(gbest(1))]);
```

```
disp(['Ki = ', num2str(gbest(2))]);
```

```
disp(['Kd = ', num2str(gbest(3))]);
```

```
%% Evaluate System with Optimized PID
```

13

```

Kp_opt = gbest(1);
Ki_opt = gbest(2);
Kd_opt = gbest(3);
PID = Kp_opt + Ki_opt / s + Kd_opt * s;
closedLoop = feedback(PID * plant_combined + Gd, 1);
t = 0:0.1:100;
step(closedLoop, t);
title('System Response with Optimized PID Gains (PSO)');
xlabel('Time (s)');
ylabel('Output');
grid on;

%% Objective Function
function cost = PID_Performance_Modified(pid_params, plant, Gd)

    Kp = pid_params(1);
    Ki = pid_params(2);
    Kd = pid_params(3);
    PID = Kp + Ki / tf('s') + Kd * tf('s');
    T_cl = feedback(PID * plant + Gd, 1);

    t = 0:0.1:100;
    [y, ~] = step(T_cl, t);

    error = abs(y - 1);
    IAE = trapz(t, error);
    cost = IAE;

```


LIST OF PUBLICATIONS

1. S. Tiwari and M. Sreejeth, "*Flow-Rate Regulation using PID Controller Tuned by Hybrid Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO)*," in Proc. 4th Int. Conf. Automation, Computing and Renewable Systems (ICACRS 2025), Pudukkottai, Tamil Nadu, India, Dec. 2025. **[Published]**
2. S. Tiwari and M. Sreejeth, "*Intelligent Flow Rate Control Using Data-Driven ANFIS: Performance Enhancement over PID under Disturbance Conditions*," in Proc. 5th Int. Conf. Emerging Frontiers in Electrical and Electronic Technologies (ICEFEEET 2026), National Institute of Technology Patna, Bihar, India, Jul. 2026. **[Accepted and to be Published]**





ICEFEET-2026: Decision regarding Submission ID: 552

1 message

Microsoft CMT <noreply@msr-cmt.org>
To: Saumya Tiwari <saumyatiwari986@gmail.com>

Tue, 12 May 2026 at 2:32 pm

Dear Saumya Tiwari ,

The organizing team of the Department of Electrical Engineering, National Institute of Technology Patna convey warm greetings for your time and effort to submit paper in the Fifth edition of the International Conference on Emerging Frontiers in Electrical and Electronic Technologies (ICEFEET-2026) is being organised at the Department of Electrical Engineering, NIT Patna on 09-10, July 2026.

We are glad to convey that your paper is accepted. The information regarding your submission may be found as follows:

Paper ID: 552
Paper Title: Intelligent Flow Rate Control Using Data-Driven ANFIS: Performance Enhancement over PID under Disturbance Condition
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