Optimized robust fuzzy sliding mode control for efficient wastewater treatment: a comprehensive study

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Article Info

Article history:

Received Apr 15, 2023
Revised Jul 30, 2023
Accepted Sep 16, 2023

Keywords:

Fuzzy logic
Jaya algorithm
Optimization
Sliding mode controller
Wastewater treatment plants

ABSTRACT

Wastewater treatment plants (WWTPs) are plagued by nonlinearities, uncertainties, and disturbances that degrade control performance and may even lead to severe instability. The WWTP control issue has received a lot of research and development during the last several decades. One well-known way of designing a resilient control system is called sliding mode control (SMC). The SMC's greatest strength lies in its innate resistance to disturbances and uncertainty. Incorporating fuzzy SMC would eliminate the chattering effect, the primary drawback of traditional sliding-mode controller, without sacrificing robustness against parametric uncertainties, modeling errors, and variable dynamic loads. This article discusses the hybridization of fuzzy logic with sliding mode control to provide highly excellent stability and accuracy in a control system. As a means of optimizing the fuzzy SMC, the gradient-free optimization technique known as the Jaya algorithm is investigated. By repeatedly altering a population of individual solutions, this population-based method can deal with both limited and unbounded optimization issues.

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1. INTRODUCTION

Water scarcity is a growing issue in many parts of the world because of factors including rising population and industrialization that increase the need for potable water. There has been a rise in the popularity of wastewater treatment plants (WWTP) as a means of preserving our planet's precious natural water supplies. However, WWTP functioning is complicated by physical, chemical, and biological phenomena unique to treatment apparatus. In addition, the problem is complicated by nonlinearity, uncertainty, and other factors [1]. A practical WWTP generally suffers from severe disturbances linked to uncertainty, that causes more often, random variations in the operating process. Industrial effluent typically contains chemicals that are hard to breakdown. Toxic effects of these chemicals on the microbial consortiums used for biodegradation mean that even trace amounts can impede the growth of these organisms and reduce the efficiency with which they can breakdown the substance [2].

Most WWTPs need to enhance their efficiency. Operating expenses are generally greater than necessary to meet regulatory effluent limitations for considerable load changes. WWTP optimization might reduce costs, but it has not been thoroughly examined. The selection of the proper control structure is necessary to ensure that plants are operating at their full potential. When deciding on a control structure, it's important to make certain value judgments about which variables should be manipulated, which should be monitored, and which inputs should be adjusted. Sliding mode control (SMC) has been utilized for a long time to assure finite-time stabilization in dynamic systems working with unknown variables (factors such as constraints upon specific disturbances, ambiguities in design variables, and mystery in the dynamic) [3]. Nevertheless, when SMC is used, the phenomenon such as chattering, it consists of oscillations with a high frequency and a tiny amplitude, becomes a risk. SMC has been extensively investigated and used for the control of nonlinear systems due to its high resilience property and quick error convergence features. Chatter attenuation without compromising robustness has been a topic of study over the past decade. There have been several recommendations made for reducing the noise, most of them use sliding mode controls.

Fuzzy control is employed either on its own or in combination with other types of control because it provides an additional, often necessary, perspective. Fuzzy SMC (FSMC) has been created offering satisfactory results. Combining fuzzy logic controller and SMC can handle plant uncertainty well. Unlike centralized control, decentralization aims to create independent controllers for every interrelated sub-system. Rao [4] suggested Jaya (Sanskrit for victory), an advanced optimization algorithm that is straightforward to implement and do not require any method-specific control parameters. Experimental evidence suggests that the Jaya approach excels at solving both constrained and unconstrained optimization problems, outperforming well-known algorithms such as genetic algorithm (GA), particle swarm optimization (PSO), differential evolution (DE), alternating best solution (ABC), and teaching-learning-based optimization algorithms [5]. Mechanical engineering, artificial neural network training, electrical engineering, structural optimization, and thermal system design are just a few of the sectors that have benefited from its fast use and development since then. This paper presents a state-of-the-art analysis of an optimization technique which is applied to enhance the performance and adaptability of the fuzzy logic system. The optimized membership functions improve the mapping between the input error signal and the output control action, leading to enhanced control performance. Jaya optimization technique can be a valuable tool for improving the performance, efficiency, and cost-effectiveness of wastewater treatment plants. By finding optimal solutions for various operational and design parameters, it assists in achieving better treatment efficiency, energy savings, and resource utilization. It also helps in reduction of wear and tear in a wastewater treatment system by optimizing operation settings, scheduling maintenance activities, balancing loads, incorporating sensor-based monitoring, and enhancing equipment redundancy. By minimizing stress and strain on the system, it promotes the longevity of the equipment, reduces maintenance costs, and ensures the reliable and efficient operation of the treatment plant. The need of an optimized and robust control approach to increase treatment efficiency is highlighted, as are the problems and concerns that are unique to wastewater treatment. An innovative control approach called optimized robust fuzzy sliding mode control (ORFSMC) is proposed by the authors.

2. WASTEWATER TREATMENT

Many parts of the world are facing a growing crisis because of dwindling freshwater supplies, expanding populations, and skyrocketing water needs [6]. So, people are becoming increasingly interested in WWTP to safeguarding our water supplies. There is a high degree of nonlinearity, uncertainty, and disturbance in WWTPs, all of which degrade control performance and can lead to catastrophic instability. An effective self-organizing sliding-mode controller (SOSMC) was suggested to attain appropriate, stable control performance with combination of SMC and fuzzy-neural lattice benefits. This is done with aim of reducing the chattering phenomenon typically associated with SOSMCs by reducing tracking errors and reducing the complexity of their underlying structures [7]. Hreiz *et al.* [8] investigated a SMC for nonlinear, multivariate systems with a latency that varies over time; the sliding surface is built with a coordinate transformation that incorporates historical values of the state variables. For optimal performance, the presented nonlinear model predictive controller (NMPC) uses both a self-organizing radial basis function neural network (SORBFNN) identifier and a multi-objective optimization strategy [9]. Using a NMPC and a unique distributed NMPC-proportional integral (PI) control structure, a unique closed-loop control of such parameters was being adaptively evaluated. The PI is responsible for controlling the process's active constraints, while the NMPC is in charge of the self-optimizing variables [10]. This paper proposes a multi-objective dynamic optimization of a small-scale wastewater treatment plant's operational strategy [11]. The main problem is that a sewage network is usually rather large, with numerous sewer pipes and pumping stations linked to one another, therefore it's difficult to mitigate sulphide levels over the whole network with a small number of dosing locations. To guarantee that the dosed chemical is distributed evenly across the pipe sections of interest, an event-driven model predictive control (EMPC) methodology was presented [12]. Considering the chattering phenomena as a limit cycle, a describing function (DF) technique yields a valuable instrument for foreseeing its presence and computing the amplitude as well as frequency of such oscillations. For the purpose of lessen the commotion, we suggest a fuzzy logic-based SMC, wherein DF technique was employed to show how much noise is dampened at the plant's output [13]. The benefits of the proposed distributed control system (DCS) architecture for the WWTP are discussed. Advanced control solutions, including multivariable adaptive and robust control algorithms, are studied to improve the control system's overall performance [14]. Sewage treatment using activated sludge can be negatively impacted by climate extremes such heavy downpours, sudden floods, and extended periods of below or above-average temperatures. The researcher proposes a robust SMC of the activated sludge treatment method for wastewater based on the ideas of binary control theory, which can be used even in extreme climates. An auxiliary input variable is used in conjunction with a SMC model to generate a consistent indication of the dilution rate, which is essential for the biodegradation process [15].

Dissolved oxygen (DO) content has a direct effect on the efficiency of wastewater treatment processes. It is a crucial part of the wastewater treatment process since it determines the final quality of the discharged water. On-line biodegradation rate assessment is useful for implementing optimal control strategies. In this research, a robust observer built on the generalized super twisting technique is employed to estimate this rate using the DO concentration as an output variable from the process [16]. There are two phenomena that work together to prevent sliding mode control from being widely used: chattering and a lot of active regulation. These two problems can be fixed at once by reducing the magnitude to the minimum value permitted by the parameters governing the sliding mode's existence [17]. Combining the static time analysis (STA) with terminal SMC, the continuous terminal SMC was suggested for uncertain systems of relative degree two. Assures third-order convergence in finite time using this approach. Shifting set with regards to the result, based solely on input concerning results and their derivative [18]. For systems subject to limited disturbances, researchers offer a new adaptive-gain twisting control (ATC) technique based on the Lyapunov theory. With the suggested ATC, the ideal or actual 2-SM may be established in a finite amount of time without the control gain being overestimated [19]. To counteract these variations, a novel disturbance rejection controller has been developed. The complexities of DO are simplified into a manageable canonical form. The dissolved oxygen dynamics are calculated by a disturbance observer, and any deviation from the controlled canonical form is corrected for by a control law [20]. For WWTP multivariable control, researchers suggest using multivariable direct self-organizing fuzzy neural network control (M-DSNNC). The structure is made up of a fuzzy neural network controller and a compensating controller. The optimum control law for a nonlinear system in general may be approximated using a fuzzy neural network [4]. To find the perfect spot where treatment efficacy and operating costs are both satisfied, researchers suggest using an intelligent multi-objective optimization control (IMOOC) based on an adaptive multi-objective differential evolution (AMODE) algorithm to sift through the data. The AMODE method is meant to enhance local search and global exploration capabilities in order to boost optimization efficiency and reach quick convergence [21]. Using an autoregressive with endogenous model, the self-tuning control implementation for a liquid process model ensures that tank levels remain on their desired trajectories, regardless of external shocks or unknowns in the system dynamics. At regular intervals, the suggested controller's parameters are automatically fine-tuned using an online recursive least square approach and a forgetting factor algorithm [22]. The Table 1 shows the comparison of different control strategies with the limitation of these strategies for adaptive situations, which is highly recommended for uncertain conditions.

Table 1. Comparison of control strategies and state-of-the-art research

Ref	Techniques used	Limitation	Remarks
[23]	Perturb and observe (P&O), Sliding mode control (SMC), Fuzzy logic control (FLC), Hill climbing search (HCS),	SMC and FLC have limitations such as the chattering effect, limited adaptability to changing environments, tuning challenges, sensitivity to model mismatch, and computational complexity, which should be considered when applying them in control systems.	The system is not highly adaptive to the change in weather conditions using Jaya optimization provides better mapping between the input error signal and the output control action, leading to better control performance.
[24]	Discrete sliding mode control (DSMC) to develop a new strategy for discrete sliding mode fuzzy control (DSMFC) in direct current (DC-DC) converter.	The proposed strategy requires human expertise in the design of the rule base, which may limit its applicability in certain scenarios.	A fuzzy rule-based system that automatically determines changes to the control signal based on the system's state and performance.
[25]	Combination of fuzzy logic (FL) approach with the robust technique discrete sliding mode control (DSMC) to develop a new strategy for DSMFC.	The paper does not compare the performance of the DSMFC strategy with other control strategies, such as proportional integral control (PID) or adaptive control.	A self-organizing sliding control strategy can give more promising result. As the laws derived by fuzzy logic is not highly adaptive
[26]	Direct torque control (DTC) with space vector modulation (SVM) and fuzzy sliding mode speed controller (FSMSC).	The paper does not compare the proposed control system with other existing control systems for sensor less induction motor drives.	The paper can be compared with other robust control such as SOSMC

3. SLIDING MODE CONTROLLER FOR WWTP

By using SMC, the dynamics of a nonlinear system may be directed towards and confined inside a target surface [27]. SMC will be used to regulate the operations of a wastewater treatment plant (WTP), with a neural network imitating the knowledge of a plant technician performing the equivalent control, and a simple function measuring the system's distance from an optimal region having its parameters optimized by a genetic algorithm. The researcher intended to suggest a sliding mode in their investigation. The proposal calls for the use of activated sludge as a means of controlling the wastewater treatment process in times of harsh weather [28], [29]. In the scope of this research, a nonlinear model with indeterminate parameter values is used to evaluate the wastewater treatment process using activated sludge. The most challenging aspect of regulating the activated sludge wastewater treatment operations arises from the fact that natural disasters may cause both the process parameters and the amount of trash that is being introduced into the system to fluctuate [30]. In order to accomplish control design, the three ordinary differential equations alongside undetermined parameters are used.

It was suggested to use a self-organizing SMC, also known as SOSMC, in order to obtain acceptable and reliable control performance of WWTP [31]. Since it makes use of fuzzy neural networks, the proposed SOSMC has impressive capabilities for learning and adapting to new environments. A self-organizing approach based on error tracking and structural complexity has been proven to be effective in decreasing chattering and enhancing control performance. Under the framework of this self-organizing system, (1) might serve as a definition of FNN and an assessment of structural risk.

$$r(tg) = \rho_1(tg) + \rho_2(tg) \quad (1)$$

Where t is the sampling interval, r is the structural risk, and tg is the tracking error at the tg^{th} sample point.

$$\rho_1(t_g) = \frac{1}{2}e(t)^T e(t) \quad (2)$$

The estimation error ρ2 (tg) is shown as (3). T is the control process's time period; K(tg) is the number of fuzzy rules on the tg^{th} sampling interval. The suggested self-organizing algorithm can make an optimal structure size decision in real time, balancing tracking error and complexity.

$$\rho_2(tg) = \frac{\sqrt{k(tg)N\,log\,Tg} - 2\,log\,k(tg)}{\sqrt{Tg}} \quad (3)$$

Biological anaerobic treatment is a cost-effective and environmentally friendly alternative to traditional chemical processes. Efficient treatment methods based on the application of anaerobic degradation of organic materials by microbial metabolism without adding oxygen to inorganic materials [32]. Biomass anaerobic digestion is a multistep process, interaction of many microorganisms in a biological process working in concert with one another. The authors perform a function estimation using a neural network $f(x(t))$.

$$f(x(t)) = W * Th(x) + \tilde{\varepsilon} \quad (4)$$

Where W* and $\tilde{\varepsilon}$ are the target and approximation errors, respectively.

While constructing a mathematical model of a WWTP may be challenging, the suggested control system is a crucial part of this experiment's multi-variable control approach. To approximate the optimal control rule for the nonlinear systems in general, the FNN is presented. In order to adjust to the unpredictability of its surroundings, the neural network must be created in a self-organizing mode [33], [34]. The international standard simulation model-1 is used for the simulations, as indicated in Figure 1.

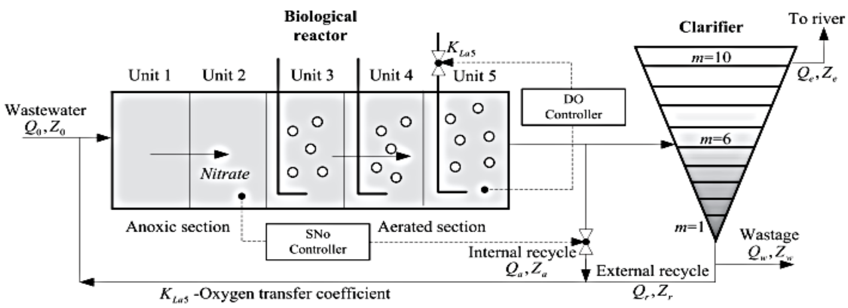

Figure 1. Architecture of BSM 1

The problem of the set-values fluctuating simultaneously in time as the rainfall scenario is ignored since dry weather data is utilized. A neural network-based technique of control has been established and been shown to be an efficient strategy for managing WWTP. Even so, the neural network's topology must be calculated accurately, and its stability must be ensured.

3.1. Optimized wastewater treatment plant

The consequences of irresponsible wastewater collection and treatment are inescapable. In addition to building a wastewater treatment plant, monitoring the effectiveness of existing treatment systems is essential for meeting stringent environmental regulations. Total biochemical oxygen demand (TBOD) is an effluent quality indicator, therefore understanding what factors influence TBOD is essential for foreseeing the treatment plant's effectiveness. Predictions of the treatment plant's efficiency were then made using the genetic algorithm-optimized neural network model, with efficient characteristics serving as network inputs [35]. Biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and pH were analyzed to determine the quality of the wastewater. The average daily air temperature, sunlight hours, and rainfall amounts were also considered.

This research utilized a parameter-free harmony search (PSF-HS) method to get the best possible outcome. The PSF-HS method has been successfully used to many benchmark issues and engineering optimization problems, such as structural design and groundwater contamination source detection, because it does not require the time-consuming procedure of algorithm parameter value setup [36]. A pool of solutions, called harmony memory (HM), is an integral part of the HS algorithm's structure. HM includes as many arbitrarily generated solutions as the harmony memory capacity. And with each new iteration, a Xnew harmony (solution ector) is produced. If the new harmony Xnew meets all the constraints and is superior to the worst harmony Xworst in HM, then Xnew is added to HM and Xworst is removed.

$$Xnew \in HM \wedge Xworst \notin HM \tag{5}$$

When compared to the standard HS method, the PSF-HS adds a new matrix—the operation type matrix (OTM). OTM records the performance data of every HM harmony. Since PSF-HS contains an extra matrix and needs an extra configuration step, it is less advantageous.

For the development of an A2-C1 type fuzzy logic system (FLS), the authors suggest the use of an enhanced ant colony optimization (IACO). Parameter optimization and rule selection are part of the design process, and by making these changes the performance of the intelligent fuzzy system may be enhanced [37], [38]. The benefits of ACO, which IACO also shares, include parallelism, intensity, positive, and negative feedback resilience and the ability to coordinate multiple objectives. It's standard to use a bio-inspired algorithm, such as a genetic algorithm or a fuzzy inference system (FIS) [39]. Hybrid methods are widely used in the industrial and manufacturing sectors. For nonlinear active mount systems, Degertekin *et al.* introduced a novel control approach based on fuzzy controller, time delay estimation, deep learning, and nondominated sorting genetic algorithm-III [40].

4. JAYA OPTIMIZATION FOR FUZZY CONTROLLER

The Jaya technique's original goal was to deal with restricted as well as unconstrained optimization functions; currently, its use is much broader. The word "victory" (Jaya) originates in Sanskrit. The concept of survival of the fittest provides some motivation for this. This suggests that the Jaya population's choices are favoring the best global solutions while ignoring the worst. The Jaya algorithm outperforms competing population-based approaches because it is both easy to implement and does not require any unique parameters. In order to regulate the motion of structures, the most popular and adaptable method is the fuzzy logic controller. A fuzzy controller's membership functions and rule base are developed by iterative experimentation, which typically necessitates the application of human knowledge and skill. Optimization of fuzzy logic has attracted more attention in recent years, controller that uses a variety of metaheuristics and techniques taken from the natural world. Wang *et al.* [41] present an innovative method for optimizing data by combining the ant lion optimizer with the Jaya algorithm.

Probabilistic algorithms are ubiquitous in optimization, and they all use the same set of tuning parameters (population size, generation count, and elite size). For certain algorithms, custom-tailored control parameters are a must. The effectiveness of the algorithms relies heavily on the accuracy with which the parameters are tuned. A small number of straightforward parameters, including population size and number of generations, are required to execute the Jaya algorithm. The Jaya algorithm melds the "fittest survive" philosophy of evolutionary algorithms with the "global optimal solution" allure of swarm intelligence methods [42].

The Jaya algorithm is a cutting-edge metaheuristic-based algorithm that combines aspects of evolutionary algorithms (EAs) with regard to the survival of the fittest principle and aspects of swarm intelligence (SI), where the swarm usually follows the chief during the search for optimal solution. The ideas behind it are elementary, and the system itself is a breeze to use. It's not derived from anything else. Positive results in the first search. It is an unconstrained algorithm. It may be adjusted easily and is both functional and comprehensive. Thus, the Jaya algorithm has seen extensive use a wide variety of optimization issues in several fields parameter extraction, and optimal power flow the virtual machine [43], knapsack problems [44], and solar cells parameter extension [45], job-shop scheduling [46], permutations and placement inconsistent scheduling in a flow shop [39], redundant systems issues with dividing resources [40], issues with putting together teams [41], face expression recognition [42], truss structures [43], and feature selection [44], plate-fin heat exchanger [45], and approximating parameters for the Li-ion battery model.

Using the default settings for its control parameters, the Jaya algorithm can be executed (population size, and generation count). Jaya generates j random starting solutions within the bounds of the process variables. Subsequently, (6) is used to stochastically update each variable in every solution.

$$X'j,k,i = Xj,k,i + r1,j,i \ (Xj,best,i - |Xj,k,i|) \ - r2,j,i \ (Xj,worst,i - |Xj,k,i|) \tag{6}$$

Each stage of the Jaya algorithm's process is explained in detail:

- Step 1: Both the Jaya method and the optimization problem need to be initialized, with the population size (N) and the number of iterations (T) being the sole algorithmic parameters.
- Step 2: Creating the base for Jaya's first population. For the Jaya algorithm, the Jaya memory is where the first population of solutions is built and stored (JM).
- Step 3: A step in the Jaya evolution. The Jaya operator is used iteratively to alter all of the JM's solutions deciding variables.
- Step 4: Simply by updating JM, the JM solutions will be refreshed at each cycle.

Iterating through Steps 3 and 4 up to some limit, called T, until the halting rule is fulfilled.

The Jaya algorithm may be easily modified and is both straightforward and effective in practice. It's been modified to work both alone and in conjunction with other projects that prioritize regional search in alongside global search. To improve upon the Jaya algorithm's efficiency and effectiveness, several other versions and hybridizations have been created [46]. Binary Jaya algorithm, discrete Jaya method, chaotic Jaya algorithm, adaptive Jaya algorithm, multi-population Jaya algorithm, parallel Jaya algorithm, fuzzy-based Jaya algorithm, and many more are among the Jaya variations that have been tweaked. When used to addressing multi-objective, multi-variable, and complicated optimization problems, the Jaya algorithm has proven to be extremely effective in both its original form and its various variations.

5. CONCLUSION

In this article, we look at the use of fuzzy logic to enhance the SMC of the wastewater treatment process. The construction of a SMC requires a clear characterization of the system's sliding surface. However, certain systems may be driven to an area instead of a surface. Fuzzy control is an effective method for designing a controller for a nonlinear system. Sliding-surface fuzzification is the foundational idea behind the proposed control method. However, developing a fuzzy system is a laborious effort, that needs the identification of numerous variables. In this study, we present the Jaya method for developing effective fuzzy systems as a means of dealing with this problem. It was sometimes necessary to augment the core Jaya algorithm with modifications to make it more effective at addressing the target issues. Jaya and its variations were chosen for integration because of their relative ease of use with other, more sophisticated systems.

ACKNOWLEDGEMENTS

This work was supported by Jain (Deemed-to-be-University) and Management, Staff and Principal of Moodlakatte Institute of Technology, Kundapura.

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