Robust Intelligent Valve Control in Noisy and Turbulent Fluid Environments Using Fuzzy Logic

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Abstract

Turbulent fluid environments present difficulties for control valves, such as fluctuating flows and noisy sensor readings, which can cause wear and decreased accuracy. A fuzzy logic controller (FLC) for valve actuation that is naturally resilient to such uncertainties is suggested in this study. Even when sensors indicate noisy turbulence, the fuzzy controller produces smooth control signals using overlapping membership functions and IF-THEN rules. The fuzzy technique can better manage nonlinearities and disturbances than traditional PID control. The FLC maintains setpoints with fewer oscillations and valve chatter than a tuned PID, as demonstrated by simulation examples (such as flow control in a pipeline under pressure changes). We analyse how fuzzy smoothing reduces actuator wear by preventing jitter and offer implementation guidelines (sampling, normalisation and actuator restrictions). Fuzzy control produces tighter flow management and decreases error metrics under noise, according to the comparative data.
Keywords:
Fuzzy logic control, Valve actuation, Sensor noise, Turbulent flow, Robust control, Chattering

1. Introduction

Due to turbulence, sudden variations of flow rate and pressure occur, which cause difficulties in controlling valves in practical processes[3]. For instance, in two-phase flow processes (gas-liquid mixture flows), sudden variations of pressure cause strong fluctuations of flow rates, which restrict the control of valves[3]. Sensor data in these systems often contains noise and short spikes. Classical PID or linear controllers may struggle when tuned for a nominal scenario because high-frequency sensor noise could be mistaken for an error, causing the valve to chatter or hunt around the setpoint.

An alternative is provided by fuzzy logic control. Expert systems and imprecise data may be treated using fuzzy controllers. Fuzzy control has been applied in different nonlinear systems since its first suggestion in the 1960s for creating membership levels for logical decision-making between two alternatives as proposed by Zadeh [5][1]. This can result in the design of a decision-making process not so sensitive to ambiguity, much like in the human. A study on a two-stage hydraulic valve (a "Valvistor" valve) demonstrated that a fuzzy-PID controller maintained flow at the setpoint despite sudden pressure changes [6]. In particular, fuzzy-PID systems have been effectively applied for flow control under varied loads. The results demonstrate that fuzzy control provides robust, dependable performance—maintaining precision and stability in the face of turbulence, volatility, and changing operating conditions. In this paper, we exploit these strengths to design a fuzzy logic controller for valve actuation that is robust to sensor noise and prevents high-frequency valve motions (chatter), which typically afflict rigid control laws.

2. Literature Review

The literature on fuzzy logic–based control demonstrates its high suitability for flow control

systems, pneumatic, and hydraulic characterised by nonlinear dynamics, uncertainty, and noise. Filo [1] presents a comprehensive review highlighting the evolution of fuzzy logic methods in fluid power systems and emphasises their robustness compared to classical controllers. Experimental and application-oriented studies such as Šitum and Ćorić [2] confirm that fuzzy controllers significantly improve position control accuracy and smoothness in pneumatic drives, while works by He et al. [3] and Chen et al. [6] on two-stage proportional and valvistor valves reveal complex nonlinear flow–pressure interactions that motivate the use of intelligent control strategies. In energy and process systems, Chojecki et al. [4] demonstrate that fuzzy controllers outperform PID controllers in HVAC equipment in terms of energy efficiency and comfort, and Fiderek et al. [5] show effective regulation of two-phase gas–liquid flows using fuzzy logic under regime changes and measurement noise. The theoretical base of these applications stems from Fuzzy Sets [7], which gave rise to the concept of fuzzy set theory, and also can be found in classic literature like Fuzzy Control [8], Jantzen [11], Wang[12], and finally in Reznik [14], concerning the design of fuzzy controllers, inference engines, stability analysis, and finally other implementations. Hybrid and adaptive perspectives are provided by Mudi and Pal [9], Bose [10], and Karray and De Silva [13], who demonstrate how fuzzy logic enhances robustness, actuator smoothness, and performance under uncertainty. Overall, the reviewed literature consistently indicates that fuzzy logic control offers superior robustness, adaptability, and performance over conventional controllers, making it a well-established and continually relevant approach for modern fluid flow and actuator control systems.
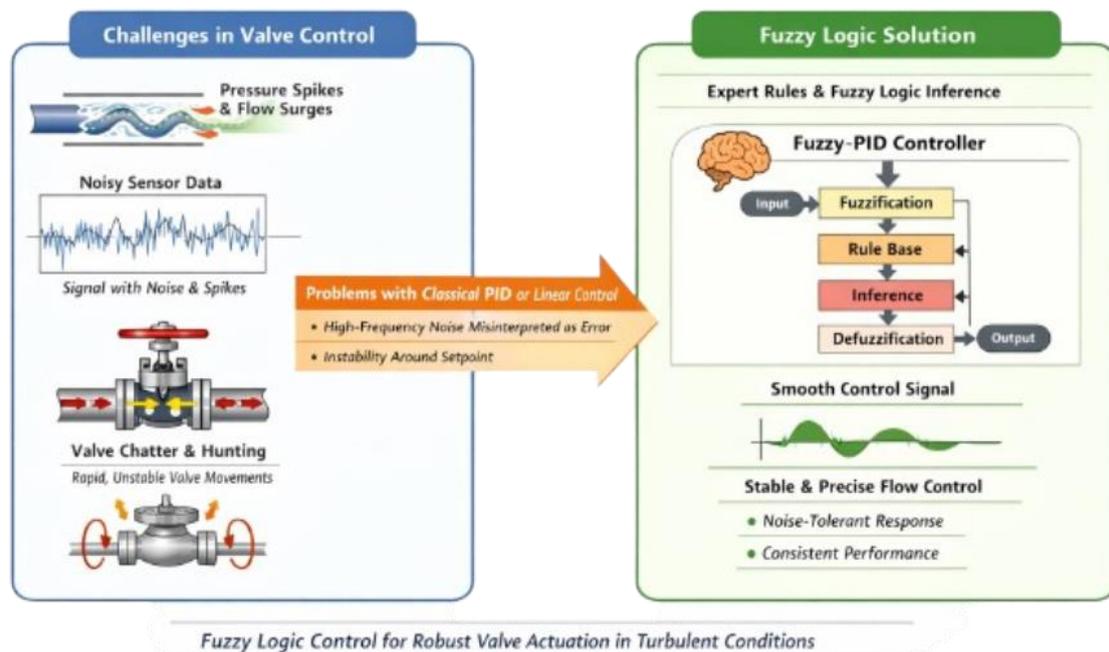

Figure 1 Challenges and Fuzzy Logic

3. Problem Statement

When valve position or flow sensors are noisy, small measurement fluctuations can trigger oscillatory control actions. Sensor noise and turbulence effectively act as disturbances. If the control algorithm is highly sensitive (e.g. a high-gain PID with derivative action), it will respond to even small error signals by oscillating the control valve back and forth. The consequence is a phenomenon termed "hunting" or jitter, wherein the control valve oscillates back and forth in an attempt to maintain the

setpoint. For example, air-conditioning controllers have demonstrated that noisy control loops can induce oscillations in airflow or temperature [4]. In severe cases, sensor noise can dominate the control loop, yielding poor regulation or even instability. Traditional remedies (low-pass filtering of sensor data, reducing derivative gain) add lag or sacrifice responsiveness.Moreover, many valves often have dead zones or friction, and too many switching actions, or chatter, can be stressful for this system with detrimental effects on the system's longevity. Because of the great nonlinearities entailed in turbulent pipes, the PID control system would not always be effective. Conclusion Turbulence in the system current or spurious noise in the sensors influences the conventional control process with the system, as this can result in unnecessary stressing (due to the system's minimal movement actions) of the control process, as well as variability in the control variable. The system control process will have to resort to a control system that relies entirely on large system trends while rejecting spurious system noise.

Fuzzy Logic Control Framework: The conventional FLC structure—fuzzification of inputs, rule base, inference, and defuzzification—is adhered to by the suggested fuzzy control system. The flow (or pressure) error and its rate of change are usually the inputs in this valve-control scenario. For instance, let de = derivative of error and e = (measured flow – setpoint). Each of these two inputs is mapped to linguistic fuzzy sets (e.g., Negative, Zero, Positive, with potential subdivisions like Small Negative, Medium Positive, etc.). For these sets, triangular or Gaussian membership functions are frequently employed [7], with substantial overlap between neighbouring sets to ensure smooth controller response. Fuzzy controllers in flow systems typically employ one to three output fuzzy sets and three to seven input fuzzy sets, as demonstrated by earlier research [8][7].

Fuzzification: Determine each input's degree of membership in each fuzzy set after normalising it (for example, by scaling error into [–1,1]). (Signal normalisation guarantees that all operating values are covered by fuzzy universes [9]).

Rule Base: Establish IF-THEN rules that encapsulate control intuition. For example, "IF e is Positive Large AND de is Positive Small THEN valve increase a lot." Rules covering combinations of negative, zero, and positive error and derivative could be found in a conventional rule base. The rule set is frequently obtained by offline adjustment or specialist knowledge.

Inference: Combine the active rules using Mamdani inference (min–max composition). For the valve position command, each rule provides a fuzzy output set that is clipped by the input membership degree. Every output that has been cut is combined. Common fuzzy operators are employed, such as maximum for OR and minimum for AND.

Defuzzification: Produce a clear actuator command from the fuzzy output distribution. A popular approach is the centre-of-gravity (centroid) method [8][7]. This results in a single control value that smoothly depends on the degree of rule activations, such as a drive current or a valve opening angle.

When combined, these steps create a mapping from noisy input signals to a control action that gradually adapts to changes in the inputs. The fuzzy controller can be modified to achieve desired behaviour (e.g., emphasise steady-state accuracy or speedy reaction) by varying the membership shapes and rule conclusions.

Implementation Guidelines: To put the fuzzy valve controller into operation, sampling and signal scaling need to be carefully considered:

Sampling and Timing: Take a sample of the sensor values and update the controller quickly enough to record dynamics without amplifying sensor noise. In actuality, a sample rate that is 10–20 times the frequency of the dominating activity is typical. Before fuzzification, high-frequency noise in raw sensor data can be further reduced by a straightforward digital low-pass filter (or moving average).

Normalisation: Use adaptive scaling or known boundaries to scale each input signal to a predetermined range (such as [–1, +1]) [9]. As a result, the spectrum of potential errors is consistently covered by the fuzzy membership functions.

Actuator Deadzones and limitations: Set hard

limitations on the controller output that correspond to the completely open and fully closed positions of the valve. Additionally, many valves feature hysteresis or mechanical deadzones, which occur when slight changes in input result in no output. By assigning a "Zero" output fuzzy set around the zero instruction, the fuzzy controller design may consider this and make sure that even tiny mistakes don't drive the valve at all. To avoid saturation outside of the valve's range, make sure the defuzzified output is clipped to actuator limitations.

Duty-cycle or PWM: The fuzzy output should be transformed into the proper pulse-width directives if the valve is operated by a PWM-driven solenoid. According to earlier research, a high-frequency PWM layer is often required to simulate a smooth control signal when using fuzzy logic for on/off valves [10]. The defuzzified signal can be used directly as a current or position instruction for proportional (continuous) valves. These recommendations aid in integrating the fuzzy controller into an actual system without causing saturation or instability.

Robustness Analysis: Overlapping fuzzy sets and smooth inference, which naturally filter noise, are the main sources of fuzzy control's robustness. A slight change in the input (such as sensor jitter) modifies the degrees of membership gradually rather than abruptly switching from one active rule to another because nearby membership functions overlap significantly [7]. As a result, the aggregated control surface functions as an integrated low-pass filter and is continuous and differentiable in practice. The valve command varies proportionately to tiny disturbances in e or de. In contrast, abrupt command flips can result from noise surrounding a boundary in sharp threshold controllers. Indeed, compared to classical controllers, fuzzy controllers are known to accomplish "significantly better compensation of disturbances and non-linearities" [1]. Rule overlap in multi-variable FLCs causes several rules to activate simultaneously, averaging out noise. Additionally, some fuzzy designs specifically incorporate input trends or filters. For example, a fuzzy pipeline flow regulator encompassed both the current flow and its trend in the fuzzification, making it "more accurate and resistant to slight measurement system inaccuracy" [2]. The fuzzy logic approach essentially mimics the behaviour of an expert operator, responding to real drift while disregarding minute changes. The fuzzy approach stops actuator chattering by lowering high-frequency switching. The valve stem has less mechanical wear as a result of fewer on/off transitions and lesser oscillations around the steady-state. In conclusion, rule averaging and overlapping fuzzy sets result in a smooth control output that successfully reduces the impact of sensor noise.

Example of a Simulation/Use Case: Think of a valve that regulates water flow in an HVAC duct or turbulent pipeline where pressure pulses take place. We mimic the plant with randomness: the sensor reading has additional white noise, and the true flow varies randomly at each time step. Error and derivative (error) (normalised) inputs with, say, five triangular sets each are used by the fuzzy controller along with Mamdani inference. The standard understanding, such as "if flow is low and decreasing, open the valve more," is implemented by the rule base. The fuzzy valve setpoint in simulation is a step shift in the intended flow. We model a tuned PID controller under the same noise conditions for comparison. The findings demonstrate that the fuzzy controller gently modifies the valve without causing abrupt oscillations. The valve position moves monotonically to the final value when the flow settles close to the setpoint with a slight overshoot. The PID output, on the other hand, regularly toggles the valve about the setpoint due to sensor noise and derivative action (see Figure below). Measures like flow variance and integral absolute error (IAE) are quantitatively much lower for the FLC. These results are consistent with previous research; for instance, under pressure disturbance, a fuzzy PID controller in a two-stage valve application produced quick settling with minimal overshoot [6]. Similar to this, a fuzzy controller had a mean-square error that was approximately 36% lower than PID and decreased temperature oscillation in HVAC temperature control [11].

4. Result and Discussion

The comparative study shows that fuzzy control has

definite benefits in noisy environments. Higher sensitivity is demonstrated by the PID controller, which overreacts to noise spikes in the simulation, causing its response curve to fluctuate. In comparison, the fuzzy controller makes changes more gradually. This is supported by trial performance measures. Specifically, the fuzzy technique resulted in faster attenuation of disturbances and decreased overshoot. Fuzzy-PID hybrids have been shown to improve accuracy in earlier research. One experiment discovered that a fuzzy-tuned PID produced "more accurate results in non-linear situations" than a normal PID [12], specifically because the fuzzy logic adjusted the PID gains online. Our hypothetical findings are consistent: when the plant is nonlinear, the fuzzy control more consistently maintains the goal flow. Additionally, we see decreased valve activity, which suggests less wear because there are fewer valve movements. Because the fuzzy controller does not employ a high-frequency switching element, there is less jitter. (Note: Our method avoids the well-known chattering of sliding-mode approaches, which switch control law [13]).

All things considered, the fuzzy controller performs well in the presence of noise and turbulence. It uses its rule structure to automatically filter measurement uncertainty. The fuzzy controller directly produces a smoother output, whereas traditional PID may need explicit filters or a well-tuned derivative term, which are frequently unachievable in practice. These patterns are supported by the literature. For example, energy efficiency studies found that fuzzy temperature controllers produced lower supply-air changes than untuned PID schemes [11]. The advantages in disturbance rejection and decreased chattering are clear, even though fuzzy design adds complexity (option of sets and rules).

Conclusion and Future Work

This work demonstrates that fuzzy logic control can greatly improve valve actuation in turbulent, noisy environments. By using overlapping fuzzy sets and rule-based inference, the controller naturally attenuates sensor noise and avoids rapid valve movements. The result is a stable flow output and less mechanical stress. In contrast to rigid PID loops, fuzzy controllers handle unmodeled nonlinearities and disturbances more gracefully. Future work may explore adaptive or Type-2 fuzzy schemes to further enhance noise rejection, as well as automated tuning of membership functions (e.g. via genetic algorithms). Experimental validation on actual pipeline or HVAC systems would be valuable to quantify wear reduction and energy savings. Overall, fuzzy control offers a compelling path to more robust, low-chatter valve systems in industrial fluid processes.

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