

ROBUSTNESS OF A FUZZY CONTROLLER VERSUS CLASSICAL PID CONTROL ON TYPICAL PLANTS

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ABSTRACT

This article deals with the robustness comparison of a Mamdani-type fuzzy controller and a classical PID controller on four typical controlled systems: proportional non-oscillatory, proportional oscillatory, proportional with transport delay, and integrating with inertia. The work responds to the lack of systematic comparison of both controller types under disturbances and parameter changes. Measurements were performed in MATLAB Simulink; PID was tuned automatically by the PID Tuner, the fuzzy controller manually by the Mamdani method with a simplified 3×3 rule base. Robustness was assessed for a position step of 10–40% and time-constant changes of 0–20%. Control quality was quantified by the IAE and ITAE summation criteria. For three of the four systems, the fuzzy controller was one to two orders of magnitude better in ITAE; for the system with transport delay, the PID was conversely two orders of magnitude better.

Keywords: fuzzy controller, PID, robustness, Mamdani, ITAE, transport delay

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1 INTRODUCTION

PID controllers have long been the standard in industrial automation. Their transfer properties are well known and tuning methods range from empirical (Ziegler-Nichols) to automated (PID Tuner in MATLAB Simulink). For linear systems with well-identifiable parameters, PID performs satisfactorily (Janošek and Farana, 2014). When the system contains nonlinearities, transport delay, or its parameters drift in time, the PID performance often drops. The work draws on agricultural applications, where systems with longer time constants occur (greenhouse temperature control, grain-silo humidity control) and the choice of a suitable controller is essential.



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1.1 Fuzzy Logic and the Mamdani FIS

Fuzzy logic, introduced by Zadeh (1965) and shaped into a controller by Mamdani and Assilian (1975), offers an alternative. Instead of binary values $\{0, 1\}$ it works with the entire interval $(0,1)$, and the central concept is the membership function, which assigns a single measurement degrees of membership in multiple fuzzy sets. A Mamdani-type Fuzzy Inference System (FIS) performs inference according to rules of the form:

$$\text{IF } e \text{ is } A_i \text{ AND } \dot{e} \text{ is } B_j \text{ THEN } u \text{ is } C_{ij}, \quad (1)$$

where e is the control error, $\dot{e}$ its derivative and u the actuation. The Mamdani FIS has a fixed input-output model: fuzzification $\rightarrow$ inference $\rightarrow$ defuzzification, with the centroid as a typical defuzzification method. An alternative to Mamdani is the Takagi-Sugeno-Kang (TSK) system (Takagi and Sugeno, 1993), which uses input functions instead of fuzzy sets in rule consequents; Mamdani was chosen in this work for its more intuitive design.

1.2 Robustness and Control-Quality Criteria

Robustness is the ability of a controller to maintain control quality under disturbances or system-parameter changes. The quality is typically quantified by summation criteria, particularly the integral of the absolute error and the time-weighted integral:

$$I_{IAE} = \int_0^\infty |e(t)| dt, \quad I_{ITAE} = \int_0^\infty t \cdot |e(t)| dt, \quad (2)$$

ITAE penalises long-lasting errors and is often more relevant for practical evaluation. Studies comparing fuzzy and PID control usually focus on a single specific task (Modrlák, 2002) and benchmark against the best-fitting setup; a systematic comparison across multiple system types appears less frequently. Providing such a comparison is the aim of this work.

2 METHODOLOGY

Four representative controlled systems were chosen. A proportional non-oscillatory second-order system with transfer:

$$G_{s1}(s) = \frac{1}{(T_1 s + 1)(T_2 s + 1)}, \quad T_1 = 10, |T_2 = 5. \quad (3)$$

A proportional oscillatory second-order system:

$$G_{s2}(s) = \frac{1}{T_0^2 s^2 + 2\xi T_0 s + 1}, \quad T_0 = 5, | \xi = 0.8. \quad (4)$$

A proportional system with transport delay:

(5)

$$G_{s3}(s) = \frac{e^{-T_d s}}{T_1 s + 1}, \quad T_1 = 25, \quad T_d = 1.$$

An integrating system with inertia:

(6)

$$G_{s4}(s) = \frac{1}{T_s(T_1 s + 1)}, \quad T_s = 10, \quad T_1 = 10.$$

Simulations ran in MATLAB Simulink. For each system a circuit was assembled in which PID and fuzzy control operated in parallel over the same plant so that the responses could be compared directly. The PID was tuned automatically by the PID Tuner with parameters *Response Time* 1.25 s and *Transient Behavior* 0.45; for the system with transport delay the *Response Time* had to be increased to 4.5 s, as lower values led to unstable response. The fuzzy controller was tuned manually by the Mamdani method with triangular membership functions for the error and its derivative (Figure 1) and a simplified 3×3 rule base (Figure 2). The tuning target was a maximum steady-state deviation of 0.003 from the setpoint as the reference criterion. Defuzzification used the centroid method. Robustness was tested in two independent scenarios: a position step of 10, 20, 30 and 40% of the input signal, and a change of time constants by 5, 10, 15 and 20% of the original value (modelling system ageing or an inaccurate model). For each scenario the overshoot, settling time and IAE and ITAE criteria were recorded.

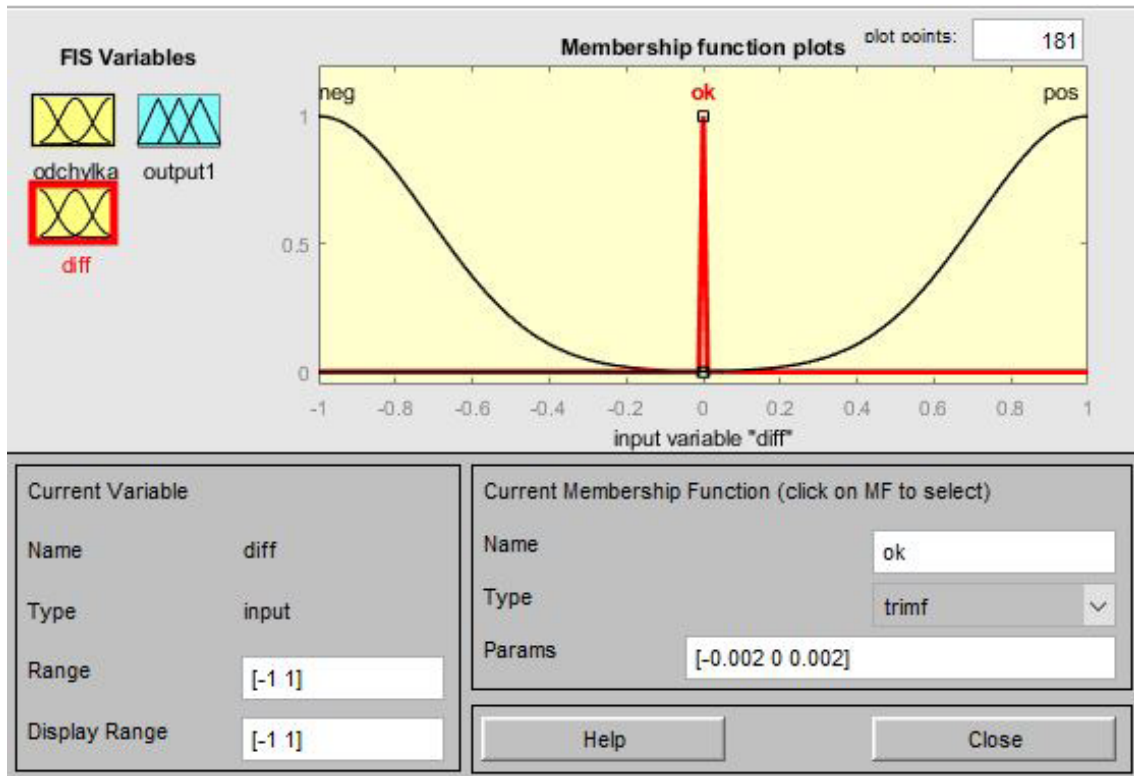
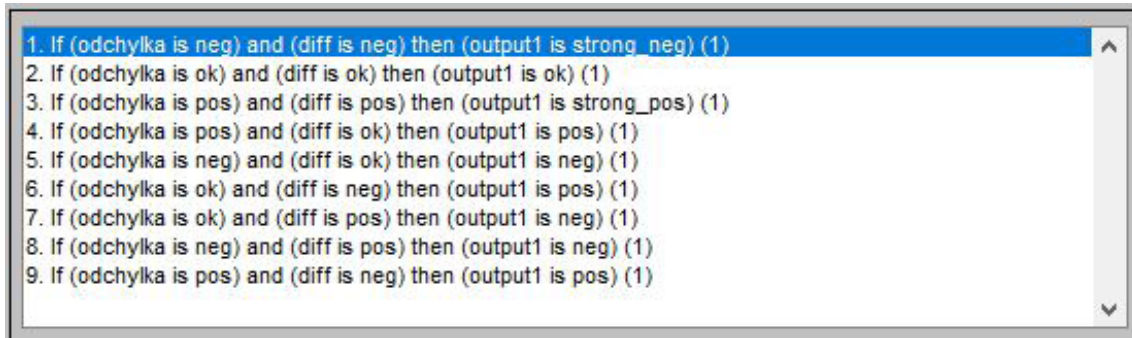


Fig. 1: Membership functions of the input "error" for the proportional non-oscillatory plant — three triangular sets *neg*, *ok*, *pos* over the range (-5,5); the narrow peak *ok* around zero ensures stabilisation in the steady state (adopted from Hebelka 2026)



1. If (odchylka is neg) and (diff is neg) then (output1 is strong_neg) (1)
2. If (odchylka is ok) and (diff is ok) then (output1 is ok) (1)
3. If (odchylka is pos) and (diff is pos) then (output1 is strong_pos) (1)
4. If (odchylka is pos) and (diff is ok) then (output1 is pos) (1)
5. If (odchylka is neg) and (diff is ok) then (output1 is neg) (1)
6. If (odchylka is ok) and (diff is neg) then (output1 is pos) (1)
7. If (odchylka is ok) and (diff is pos) then (output1 is neg) (1)
8. If (odchylka is neg) and (diff is pos) then (output1 is neg) (1)
9. If (odchylka is pos) and (diff is neg) then (output1 is pos) (1)

Fig. 2: Mamdani fuzzy controller rule base — nine IF (error × derivative) THEN action rules for the proportional non-oscillatory plant (adopted from Hebelka 2026).

3 RESULTS

The resulting PID parameters after tuning by the PID Tuner are summarised in Table 1.

Tab. 1 PID controller tuning by the PID Tuner

System	K _p	K _I	K _D
Proportional non-oscillatory	11.36	2.00	13.75
Proportional oscillatory	19.33	2.17	37.08
Proportional with transport delay	11.46	0.95	−3.28
Integrating with inertia	6.83	0.66	15.41

The negative derivative gain for the system with transport delay reflects that the PID Tuner chose a markedly less aggressive action to compensate the dead time.

Proportional non-oscillatory. PID overshoot grew roughly linearly with the error (0.080 → 0.317 for 10 → 40%), the fuzzy controller saturated around 0.16. Settling times were 4.6–15.7 s for PID and 0.4–0.82 s for fuzzy. ITAE for fuzzy was 1.30–2.15 versus 14.52–42.16 for PID. The fuzzy controller is more robust here.

Proportional oscillatory. PID overshoot 0.098–0.388 (linear with error), fuzzy 0.116–0.157 (asymptotically stable). Settling times PID 17.9–27.4 s, fuzzy 0.75–1.26 s. ITAE fuzzy 3.26–5.77 versus 37.65–98.55 for PID. The fuzzy controller is more robust.

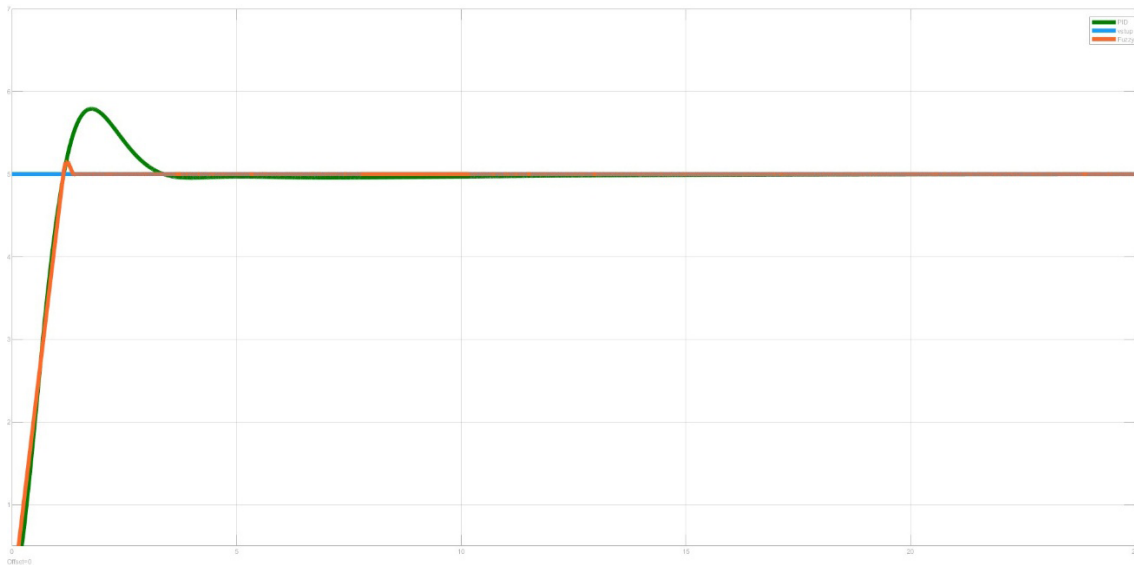
Proportional with transport delay. The third test reversed the result. PID settling time 34.7–48.5 s, fuzzy 83.2–218.3 s — that is, 2.5–4.5× worse. IAE PID 19.1–24.3, fuzzy 245.7–385.5. ITAE PID 221–570, fuzzy 15 092–57 856, two orders of magnitude worse. PID is more robust here.

Integrating with inertia. PID overshoot 0.109–0.432, fuzzy 0.091–0.157. Settling times PID 10.2–12.2 s, fuzzy 0.44–0.85 s. ITAE PID 47.6–113.6, fuzzy 1.21–2.00 — two orders of magnitude better for fuzzy (Hebelka, 2026).

A comparison summary for all four systems is shown in Table 2; a typical time response is shown in Figure 3.

Tab. 2 Robustness summary — which controller wins per system

System	More robust controller	ITAE (PID / fuzzy)
Proportional non-oscillatory	Fuzzy	14–42 / 1.3–2.2
Proportional oscillatory	Fuzzy	38–99 / 3.3–5.8
Proportional with transport delay	PID	221–570 / 15 092–57 856
Integrating with inertia	Fuzzy	48–114 / 1.2–2.0

**Fig. 3:** Time response of PID (green) and fuzzy (orange) controllers for the proportional non-oscillatory system under a unit step; blue is the setpoint (adopted from Hebelka 2026).

4 DISCUSSION

The results confirm the general statement in the literature that fuzzy controllers usually outperform PID on nonlinear or poorly modelled tasks. The system with transport delay is an important exception. Dead time is tricky from a controller's standpoint: an action taken at time t shows up on the controlled variable only at $t+T_d$. If the controller reacts only to the instantaneous error and its derivative, it easily overshoots — keeping the action longer than necessary because it cannot yet see the effect. The PID copes with this via a negative K_D , which effectively brakes the action before the error appears. The Mamdani fuzzy controller with a simplified 3×3 rule base cannot achieve such fine behaviour; its rule base reacts to coarse categories, and damping the dead time would require substantially richer rules. A suitable path forward is a Smith predictor combined with fuzzy logic or a neuro-fuzzy controller.

A second point concerns the tuning method. PID was tuned automatically by the PID Tuner, which yields an essentially optimal result; the fuzzy controller was tuned by manual trial and error. This is fair in the sense that a manually tuned PID typically performs worse than a Tuner-tuned one — but it does not allow a fully symmetric comparison. Future work could employ optimisation methods for automated fuzzy tuning (for example a genetic algorithm to search the membership-function layout).

5 CONCLUSION

The work compared a Mamdani-type fuzzy controller and a classical PID controller on four typical controlled systems. For each system both controllers were tuned by the same methodology and tested under a 10–40% position step and a 0–20% change of time constants. Three findings deserve attention. For three of the four systems (proportional non-oscillatory, oscillatory, integrating with inertia) the fuzzy controller was more robust — ITAE typically 10–20× better than PID, settling time one order of magnitude shorter. For the system with transport delay PID was more robust — ITAE two orders of magnitude better (220–570 versus 15 000–58 000); a fuzzy controller built on the instantaneous error and its derivative cannot handle dead time without a substantially richer rule base. The choice of the quality metric materially affects interpretation — ITAE, which penalises late errors, better matches user perception than settling time or IAE alone. Future expansions may include automated fuzzy tuning by a genetic algorithm and a combination with predictive techniques for systems with transport delay.

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