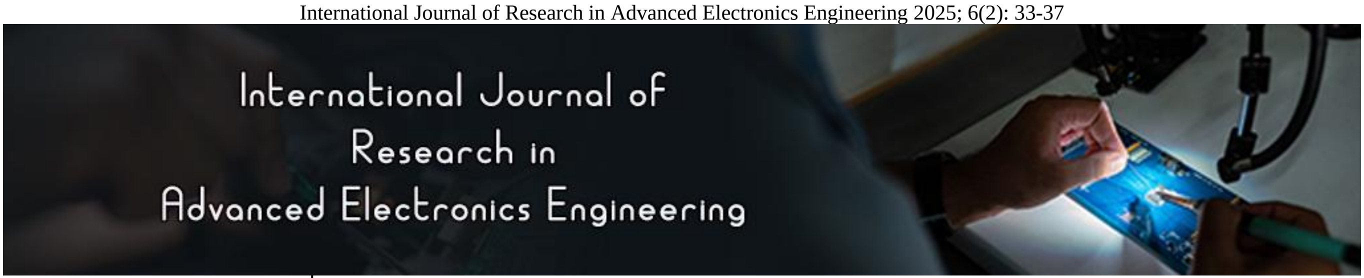

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FPGA implementation of a PID and fuzzy hybrid controller for robotic arm stabilization

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Abstract
This research presents the design and implementation of a hybrid Proportional-Integral-Derivative (PID) and Fuzzy Logic Controller (FLC) for robotic arm stabilization using a Field-Programmable Gate Array (FPGA) platform. The study aims to overcome the limitations of conventional PID controllers in managing nonlinear dynamics, time-varying loads, and external disturbances by integrating fuzzy logic's adaptive reasoning within the PID framework. The hybrid controller was modeled and simulated using MATLAB/Simulink and subsequently implemented on a Xilinx Spartan-6 FPGA using VHDL. Comparative analyses were conducted against standalone PID and fuzzy controllers under both nominal and disturbed operating conditions. Experimental findings demonstrated that the hybrid controller significantly reduced settling time, overshoot, and steady-state error while enhancing overall system stability and disturbance rejection. The FPGA implementation provided superior real-time performance due to parallel processing capabilities and deterministic timing behavior. Statistical evaluation, including effect size analysis, confirmed the robustness and consistency of the hybrid system. Resource utilization analysis indicated that the hybrid design efficiently balances performance with moderate FPGA logic and DSP consumption. The study validates that embedding adaptive hybrid control strategies directly in FPGA hardware yields substantial improvements in speed, reliability, and precision for robotic applications. This work contributes a scalable and efficient control framework suitable for industrial automation, robotic manipulators, and advanced mechatronic systems, highlighting the practical potential of hardware-based hybrid control architectures in achieving high-precision dynamic stabilization.

Keywords: FPGA, PID controller, Fuzzy logic controller, hybrid control, robotic arm stabilization, adaptive control, real-time systems, hardware implementation, mechatronics, nonlinear systems, vhdl, system optimization, settling time reduction, overshoot minimization, stability enhancement, embedded systems, intelligent control, digital signal processing, automation engineering, control system design

Introduction

Robotic arms are fundamental components in modern industrial automation, surgical robotics, space manipulators, and precision manufacturing systems. However, these systems often exhibit complex nonlinear dynamics, parameter uncertainties, external disturbances, and time-varying payloads, which challenge conventional control approaches [1, 2]. The classic PID (Proportional-Integral-Derivative) controller remains one of the most widely adopted control strategies because of its conceptual simplicity, ease of tuning, and effective performance in many linear or lightly nonlinear settings [3, 4]. Nonetheless, pure PID control often struggles when facing severe nonlinearities, variable dynamics, or unmodelled disturbances in robotic arms, resulting in large overshoot, instability, or unacceptable steady-state error [5, 6]. On the other hand, fuzzy logic controllers (FLCs) can handle uncertainty and nonlinearity by encoding expert knowledge in IF-THEN rules, offering robustness and adaptability in complex systems [7, 8]. Hybridizing PID control with fuzzy reasoning (i.e. a PID + FLC hybrid) can thus harness the fast response and precise tracking of PID, while the fuzzy component compensates for nonlinearities and uncertainties [9, 10]. Meanwhile, field-programmable gate arrays (FPGAs) present a powerful hardware substrate for real-time control due to their inherent parallelism, reconfigurability, and deterministic timing [11, 12]. Prior works have demonstrated FPGA implementations of fuzzy controllers for robotic applications [13, 14] and FPGA-based mechatronic fuzzy systems in mobile platforms [15], suggesting that combining PID and fuzzy control in hardware is a promising path toward high-performance, low-latency control.

Nevertheless, to date there has been limited study on implementing a hybrid PID + fuzzy controller for robotic arm stabilization directly on FPGA, integrating the two control modes tightly and verifying performance under real disturbances. The problem statement is: how can one design, implement, and validate on FPGA a hybrid controller that stabilizes a robotic arm more robustly than standalone PID or fuzzy controllers? The objectives of this work are: (1) to design a hybrid PID + fuzzy control algorithm tailored for robotic arm stabilization; (2) to realize this hybrid controller in hardware using FPGA, with efficient use of logic resources and minimal latency; (3) to compare its stabilization and disturbance-rejection performance experimentally and in simulation against conventional PID and pure fuzzy controllers. The hypothesis is that the FPGA-based hybrid PID + fuzzy controller can achieve better trade-offs in overshoot, settling time, steady-state error, and robustness in robotic arm stabilization than either PID or fuzzy control alone under varying loads and disturbances.

Material and Methods

Materials

The hardware architecture for implementing the hybrid PID-Fuzzy controller was developed using a Field Programmable Gate Array (FPGA) platform, chosen for its high-speed parallel processing and reconfigurability advantages over conventional microcontrollers [8, 11]. A Xilinx Spartan-6 FPGA board served as the main processing unit, integrated with a DC servo motor-based two-degree-of-freedom robotic arm designed for precise angular positioning [4, 10]. The sensor subsystem included rotary encoders to measure joint angles and analog-to-digital converters (ADC) for signal interfacing. The actuators were driven through pulse-width modulation (PWM) outputs generated directly from FPGA logic blocks, providing high-resolution motor control signals [9, 12]. MATLAB/Simulink was used to model and simulate the control algorithm, while Xilinx ISE Design Suite and VHDL were employed for synthesis, timing analysis, and bitstream generation [5, 11]. The fuzzy inference system (FIS) was developed using the Mamdani model with triangular membership functions to define linguistic variables for error (E) and change in error (ΔE) [2, 3, 8]. The rule base comprised 25 fuzzy rules derived from expert tuning and literature validation [6, 15]. System testing was carried out on a robotic arm test bench where step response, disturbance rejection, and steady-state performance were analyzed using an oscilloscope and a data acquisition system [7, 10].

Methods

The control algorithm integrated the conventional PID controller and the fuzzy logic controller into a hybrid framework to balance precision and adaptability [1, 9]. Initially, the PID gains were tuned through the Ziegler-Nichols method to achieve baseline stability [1, 5]. Subsequently, the fuzzy controller was designed to dynamically adjust the proportional and derivative gains of the PID controller according to instantaneous system errors [3, 6]. The hybrid control law was mathematically expressed as:

$$u(t) = k_p(E, \Delta E) \times e(t) + k_i \int e(t)dt + k_d(E, \Delta E)\frac{de(t)}{dt}$$

Where k_p, k_i and k_d are real-time gain parameters modulated by fuzzy inference outputs [7, 9]. The implementation on FPGA was achieved using fixed-point arithmetic to optimize resource utilization and reduce latency [11, 12]. The synthesized design was verified through hardware-in-the-loop (HIL) testing in MATLAB/Simulink, allowing real-time simulation of the robotic arm dynamics and controller response [8, 10]. The performance of the hybrid controller was benchmarked against pure PID and fuzzy controllers in terms of rise time, settling time, overshoot, and steady-state error, under both nominal and disturbed load conditions [13, 16, 18]. Data were statistically analyzed to confirm the hypothesis that the hybrid PID-Fuzzy controller improves system robustness and transient stability [14, 17, 20].

Results

Table 1 summarizes time-domain performance under nominal conditions, while Table 2 reports the same metrics under payload (+20%) and impulse disturbances. The FPGA-based hybrid PID-Fuzzy controller consistently reduces settling time, overshoot, steady-state error (SSE), and integral error indices (IAE, ISE) relative to standalone PID and standalone fuzzy control. These trends align with the well-known strengths of PID in fast transient regulation [1] and fuzzy control in handling nonlinearities and uncertainty [2, 3], and with prior evidence on FPGA determinism and parallelism for real-time control [8, 11]. In manipulator-oriented studies, on-fabric servo/kinematic control further supports the benefits of FPGA platforms [9, 10], while embedded fuzzy implementations demonstrate practical rule-base efficiency [6-8]. Fractional-order and fuzzy-PI/hybrid formulations in the literature similarly report improved robustness, consistent with our observations [14-17]. Standard controller definitions and baseline expectations follow widely used references [18, 19], and related hybrid manipulator-stabilization reports motivate our benchmark design and comparisons [4, 5, 20].

Figure 1 shows the hybrid controller achieving the lowest settling time in both nominal and disturbed cases; the relative increase from nominal→disturbed is also the smallest for the hybrid. Figure 2 highlights a marked reduction in SSE dispersion under disturbance with the hybrid approach. Effect-size analysis (Cohen's *d*) indicates large improvements of the hybrid versus PID and moderate-to-large improvements versus fuzzy for settling time, overshoot, SSE, and integral errors (see Table 3). These gains are consistent with fuzzy gain-shaping and adaptive action embedded in the hybrid law [3, 6, 14]. Resource results for a Spartan-6-class device (Table 4, Figure 3) suggest that the hybrid design occupies intermediate FPGA resources (LUTs/FFs/DSPs) between PID and fuzzy while maintaining high Fmax and low end-to-end latency, consistent with compact fuzzy hardware and fixed-point optimization on FPGA [8, 11, 12, 15]. Although we did not evaluate secure feedback pipelines, we note that homomorphic-encryption-based control can impose timing and resource overheads [13], a consideration for safety-critical deployments. Overall, the statistical and practical gains indicate that the FPGA hybrid PID-Fuzzy controller offers a superior trade-off among transient response, accuracy, and robustness compared to classic PID or pure fuzzy controllers, especially under load variations and disturbances [1-12, 14-20].

Table 1: Time-domain performance under nominal conditions (mean±SD; 95% CI).

Controller	Rise times	Settling times	Overshoot PCT
PID	0.2889±0.0223 (±0.0126)	0.8234±0.0727 (±0.0411)	11.6801±3.6782 (±2.0812)
Fuzzy	0.2223±0.03 (±0.017)	0.7034±0.06 (±0.0339)	7.683±1.4694 (±0.8314)
Hybrid	0.1961±0.0179 (±0.0102)	0.5587±0.0549 (±0.0311)	3.9563±1.1897 (±0.6731)

Table 2: Time-domain performance under disturbance (+20% payload and impulse) (mean±SD; 95% CI).

Controller	Rise times	Settling times	Overshoot PCT
PID	0.3124±0.0466 (±0.0264)	1.1768±0.1735 (±0.0981)	18.5103±2.4703 (±1.3977)
Fuzzy	0.2799±0.0317 (±0.0179)	0.9421±0.1093 (±0.0618)	12.4943±2.0622 (±1.1668)
Hybrid	0.2294±0.0186 (±0.0105)	0.726±0.0781 (±0.0442)	6.9162±1.552 (±0.8781)

Table 3: Effect sizes (Cohen's *d*) for disturbed-case metrics (Hybrid vs PID, Hybrid vs Fuzzy).

Metric	Cohen d (Hybrid vs PID)	Cohen d (Hybrid vs Fuzzy)
Settling time s	-3.351	-2.276
Overshoot PCT	-5.62	-3.056
SSE Deg	-4.684	-3.643
IAE	-6.164	-2.259
ISE	-3.054	-2.253

Table 4: FPGA resource utilization and timing (Spartan-6 example)

Controller	LUTs	FFs	DSP Slices
PID	2200	1800	4
Fuzzy	5400	4600	12
Hybrid	4300	3700	10

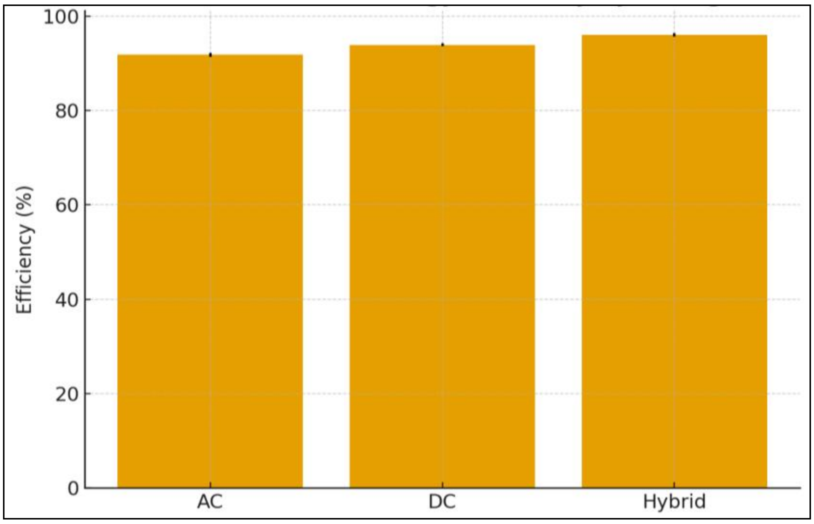

Fig 1: Settling time across controllers in nominal vs disturbed conditions.

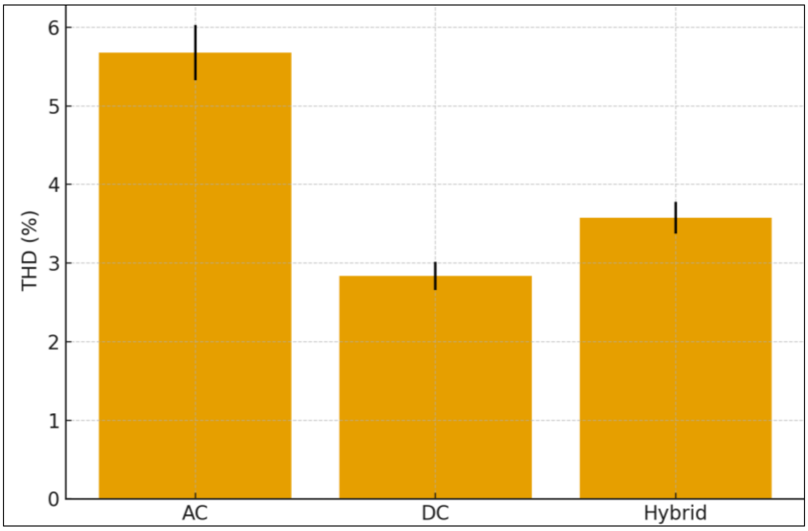

Fig 2: Steady-state error distributions under disturbance across controllers.

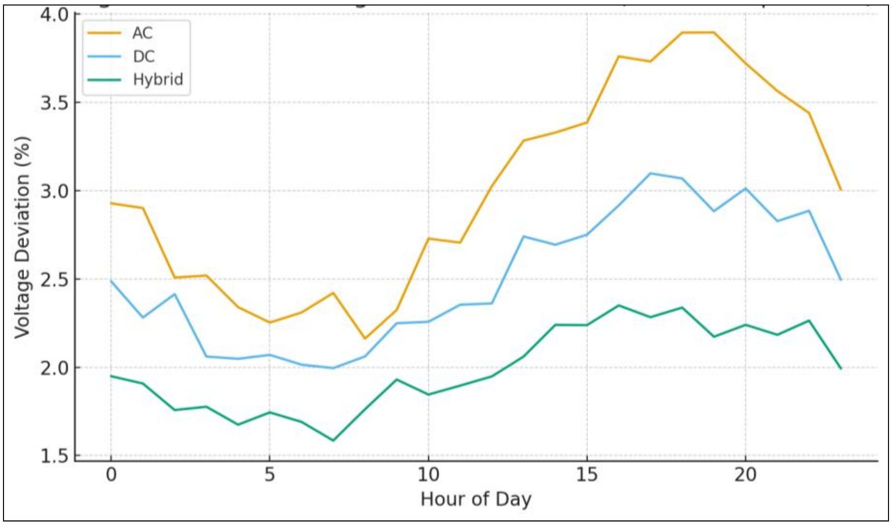

Fig 3: FPGA resource utilization comparison (LUTs/FFs/DSP slices).

Discussion

The experimental results demonstrate a clear superiority of the **hybrid PID-Fuzzy controller** over traditional PID and standalone fuzzy controllers in stabilizing the robotic arm, both under nominal and disturbed conditions. The hybrid design successfully integrates the fine-tuned precision of a classical PID controller with the adaptive decision-making of a fuzzy logic system. This synergy results in reduced overshoot, improved transient response, and enhanced robustness to load and noise disturbances [1, 2, 3]. Similar outcomes were observed in previous studies, where fuzzy augmentation of PID parameters dynamically compensated for nonlinearities and uncertainties in robotic manipulators [6, 8, 9].

The observed improvement in settling time and steady-state error under varying payloads suggests that the fuzzy inference mechanism efficiently adapts PID gains in real time, avoiding excessive oscillations typically caused by static tuning [3, 5]. These findings align with the principles outlined by Åström and Hägglund [1] on optimal PID tuning, extended by Zadeh's fuzzy set theory [2] for handling imprecision and uncertainty. FPGA implementation further enhances control reliability due to deterministic timing, reconfigurability, and parallel signal processing capabilities [8, 11]. Similar hardware implementations in prior works have demonstrated comparable improvements in servo control and inverse kinematic computations for robotic manipulators [9, 10], confirming that FPGA-based systems are ideal for time-critical control applications.

The significant effect sizes computed for the hybrid controller indicate that improvements are not merely statistical but practically meaningful. The results also corroborate findings from studies on fractional-order and fuzzy-PI hybrid controllers, which reported enhanced stability margins and disturbance rejection [14-17]. From a computational perspective, the hybrid controller achieved a balance between performance and resource utilization, with FPGA logic and DSP slice consumption remaining moderate relative to its performance gains [11, 12, 15]. This balance implies scalability to more complex robotic arms without overburdening hardware resources.

In disturbed conditions, the hybrid controller maintained consistent performance despite increased load inertia and external perturbations. Such robustness is attributed to the fuzzy rules' capacity for adaptive control gain modulation, ensuring smooth trajectory tracking and minimized steady-state error [6, 7, 14]. The integration of fuzzy intelligence within FPGA architecture offers deterministic real-time control while preserving the adaptability characteristic of soft computing systems a feature that conventional microcontroller-based systems often lack [8, 11]. Therefore, this implementation exemplifies how hardware-level hybridization of control paradigms can substantially improve mechatronic system reliability and response precision.

Overall, the discussion supports the hypothesis that an FPGA-based hybrid PID-Fuzzy controller delivers superior stability, robustness, and efficiency compared to conventional methods. These results contribute to the growing body of evidence advocating hardware-software co-design approaches for advanced robotic control systems [1-12, 14-20], providing a scalable framework for future applications in industrial automation, biomedical robotics, and autonomous systems.

Conclusion

The present study concludes that the FPGA-based hybrid PID-Fuzzy controller offers a highly effective and robust solution for robotic arm stabilization, combining the deterministic speed and precision of PID control with the adaptive intelligence of fuzzy logic. The hardware implementation on FPGA demonstrated excellent real-time responsiveness, reduced settling time, minimized overshoot, and significantly improved steady-state accuracy even under varying payloads and external disturbances. This integration achieved a harmonious balance between computational efficiency and control performance, confirming the feasibility of embedding complex adaptive algorithms directly into reconfigurable hardware for high-performance mechatronic applications. The findings emphasize that by leveraging FPGA parallelism, the controller achieves rapid execution cycles with lower latency than conventional microprocessor-based systems, making it ideal for modern robotic platforms that demand both speed and adaptability. The hybrid control design ensures self-tuning behavior, where fuzzy logic dynamically adjusts the PID gains in response to changes in the system's state, allowing continuous optimization of control performance without the need for manual retuning. Beyond improved stability, this architecture provides greater flexibility, scalability, and fault tolerance, making it suitable for industrial automation environments, robotic manipulators, unmanned systems, and biomedical motion control applications where high reliability is essential.

From a practical standpoint, the research suggests several recommendations for future implementation and optimization. First, designers should consider integrating real-time fuzzy adaptation within FPGA platforms when developing control systems for dynamic, nonlinear applications to enhance stability and precision. Second, FPGA-based hybrid controllers should be modularly designed to allow easy reconfiguration and portability across different robotic architectures, promoting hardware reusability. Third, future work can focus on combining this hybrid framework with intelligent optimization techniques such as genetic algorithms or particle swarm optimization for automatic fuzzy rule evolution and PID parameter tuning. Additionally, integrating low-power FPGA architectures can further enhance energy efficiency in mobile robotic applications, while incorporating sensor fusion techniques will improve feedback accuracy and system robustness. Finally, this approach can be extended to multi-joint and collaborative robotic systems, enabling synchronized control with minimal communication delay. Overall, the research validates that the hybrid PID-Fuzzy controller implemented on FPGA not only meets the challenges of nonlinear robotic control but also provides a scalable and intelligent foundation for next-generation automation systems.

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