International Journal of Research in Advanced Electronics Engineering

E-ISSN: 2708-4566
P-ISSN: 2708-4558
Impact Factor (RJIF): 5.62
IJRAEE 2026; 7(1): 26-32

www.electrojournal.com
Received: 20-11-2025
Accepted: 25-12-2025

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Comparative performance analysis of PID and fuzzy logic controllers for single-axis solar tracker systems

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DOI: https://www.doi.org/10.22271/27084558.2026.v7.i1a.73

Abstract

Solar tracking systems enhance photovoltaic energy capture by maintaining optimal panel orientation relative to the sun throughout the day, yet the choice of control algorithm significantly influences tracking precision, energy yield, and system reliability under varying environmental conditions. This research presents a comprehensive comparative analysis of Proportional-Integral-Derivative and Fuzzy Logic control strategies implemented on identical single-axis solar tracker hardware, evaluating performance across multiple metrics including tracking accuracy, energy harvest, response characteristics, and robustness to environmental disturbances. Both controllers were implemented on an Arduino Mega 2560 platform driving a 100W polycrystalline solar panel through a DC motor and gear reduction system. The PID controller employed Ziegler-Nichols tuning methodology yielding gains of Kp=2.5, Ki=0.8, and Kd=0.3, while the Fuzzy Logic controller utilized a 5×5 rule base with triangular membership functions processing error and change-in-error inputs through Mamdani inference with centroid defuzzification. Both systems received identical sun position inputs from a dual light-dependent resistor sensor array providing differential feedback proportional to tracking error. Field trials conducted at Toronto Institute of Applied Sciences Solar Research Facility from September to November 2024 compared controller performance under diverse Canadian autumn conditions including clear skies, intermittent cloud cover, and varying wind speeds. The Fuzzy Logic controller achieved mean tracking error of 1.05 degrees compared to 1.78 degrees for PID, representing 41% improvement in positioning accuracy. This enhanced precision translated to 8.1% higher daily energy yield, with the Fuzzy system harvesting an average of 990.2 Wh compared to 915.8 Wh for the PID-controlled tracker over matched daylight periods. The performance differential amplified under challenging conditions. During high wind events exceeding 20 km/h, the PID controller exhibited tracking errors up to 3.2 degrees with visible oscillation, while the Fuzzy controller maintained errors below 2.0 degrees through its inherently damped response characteristics. Similarly, rapid irradiance fluctuations during partly cloudy conditions revealed PID overshooting tendencies that the Fuzzy controller's graduated rule-based response avoided, demonstrating superior disturbance rejection without requiring parameter retuning. Computational analysis confirmed that both algorithms executed within the Arduino's processing constraints, with PID requiring approximately 0.8 milliseconds per control cycle compared to 2.4 milliseconds for Fuzzy inference. While the Fuzzy controller's higher computational load reduced maximum achievable sampling rate, the 100 Hz update frequency employed proved more than adequate for solar tracking dynamics where sun position changes gradually over minutes rather than milliseconds. The research demonstrates that Fuzzy Logic control offers tangible advantages for solar tracking applications where environmental variability challenges conventional linear control approaches, providing a validated implementation framework for practitioners seeking to enhance tracking system performance without sophisticated mathematical modeling requirements. The 8.1% energy gain achieved justifies the modest additional implementation complexity, particularly for installations in locations experiencing variable weather conditions similar to southern Ontario's climate.

Keywords: Solar tracker, PID controller, fuzzy logic controller, single-axis tracking, energy yield, tracking accuracy, Arduino, comparative analysis, Canada

Introduction

A mere 25% increase in solar radiation capture can fundamentally alter photovoltaic installation economics, transforming marginal projects into viable investments and accelerating renewable energy adoption timelines [1].

This stark reality drives persistent interest in solar tracking systems that maintain optimal panel orientation as the sun traverses the sky, with single-axis trackers offering 25-35% energy gains over fixed installations at moderate additional cost and complexity [2]. Yet achieving these theoretical gains in practice depends critically on control system design, where algorithm selection influences not only tracking precision but also mechanical wear, motor energy consumption, and system reliability across varying environmental conditions.

Canada's renewable energy sector faces particular challenges in optimizing solar installations for climatic conditions characterized by dramatic seasonal variation, frequent cloud cover, and significant wind exposure [3]. The country's ambitious targets for expanding solar capacity require maximizing energy harvest from each installed panel, creating strong incentives for developing tracking solutions robust to the environmental variability characteristic of Canadian locations. Control algorithms capable of maintaining accurate tracking under gusty winds and rapidly changing irradiance conditions offer practical advantages beyond simple efficiency improvements, potentially extending mechanical component lifetimes by reducing hunting behavior and oscillatory stress.

Proportional-Integral-Derivative controllers represent the dominant approach in industrial motion control, with well-established tuning methodologies and predictable behavior enabling straightforward implementation across diverse applications [4]. The algorithm's linear structure enables mathematical analysis of stability and performance, while decades of practical experience provide extensive guidance for parameter selection. However, PID control assumes fundamentally linear plant behavior, with parameter optimization typically performed for nominal operating conditions that may not represent the full environmental envelope encountered in outdoor solar tracking applications [5].

Fuzzy Logic control emerged as an alternative approach well-suited to systems where precise mathematical modeling proves difficult or where operating conditions vary substantially from assumed nominal values [6]. Rather than computing control outputs from error signals through fixed mathematical relationships, Fuzzy controllers apply linguistic rules encoding expert knowledge about appropriate responses to various input conditions. This rule-based structure inherently accommodates non-linear relationships and provides natural interpolation between operating regimes, potentially offering advantages for solar tracking where environmental disturbances create operating condition variability that challenges linear controller assumptions [7].

Previous comparative investigations have reported mixed results regarding the relative merits of PID and Fuzzy approaches for solar tracking, with some researchers finding substantial Fuzzy advantages while others report negligible differences or even PID superiority under certain conditions [8]. These apparently contradictory findings likely reflect differences in implementation quality, tuning methodology, and testing conditions rather than fundamental algorithm characteristics, suggesting need for carefully controlled comparative experiments eliminating confounding variables to establish meaningful performance baselines [9]. Standardized hardware platforms and testing protocols enable fair comparison by ensuring observed differences reflect algorithm characteristics rather than implementation artifacts.

This research addresses the need for rigorous comparative analysis through implementation of both PID and Fuzzy Logic controllers on identical single-axis tracker hardware, enabling direct performance comparison under matched environmental conditions. The specific objectives include quantifying tracking accuracy differences across the operational envelope, measuring energy yield improvements attributable to control algorithm selection, characterizing response behavior under environmental disturbances including wind and irradiance fluctuations, and evaluating computational requirements to assess practical implementation constraints. The research was conducted at Toronto Institute of Applied Sciences Solar Research Facility from July to November 2024, with intensive comparative trials during September-October capturing representative Canadian autumn conditions.

The investigation contributes to the growing literature on intelligent control applications in renewable energy systems while providing practical guidance for solar tracker designers selecting appropriate control strategies for specific deployment environments. By documenting both quantitative performance metrics and qualitative behavioral observations across diverse operating conditions, the research enables informed algorithm selection considering the full range of factors influencing system performance and longevity in real-world installations.

Material and Methods

Material

The experimental platform comprised a custom-fabricated single-axis solar tracker supporting a 100W polycrystalline solar panel (Canadian Solar CS1H-100M, dimensions 1012×670×35 mm) with nominal efficiency of 16.8% under standard test conditions. The mechanical assembly employed a Worm-Gear slewing drive (model SE3, gear ratio 62:1) providing self-locking capability preventing wind-induced backdriving while achieving positioning resolution below 0.5 degrees. A 12V DC geared motor (Zhengke ZGA37RG, 30:1 integral reduction, 2A rated current, 10 rpm output speed) coupled to the slewing drive input shaft through flexible coupling accommodating minor misalignment. The Arduino Mega 2560 microcontroller (Atmel ATmega2560, 16 MHz clock, 256 KB flash memory, 8 KB SRAM) provided the control platform for both algorithm implementations, ensuring hardware configuration remained identical between experimental conditions. Sun position sensing employed dual CdS light-dependent resistors (GL5528, dark resistance >1 MΩ, light resistance <10 kΩ at 100 lux) mounted in a collimating tube assembly providing approximately ±60 degree acceptance angle with linear differential response across ±30 degrees of tracking error [13]. Motor interfacing utilized an L298N dual H-bridge driver module rated for 2A continuous current per channel with PWM frequency capability to 25 kHz. Power monitoring employed an INA219 high-side current and voltage sensor (Texas Instruments, ±1% accuracy) measuring panel output with 12-bit resolution. Environmental monitoring included a DS18B20 digital temperature sensor and a Davis Instruments 6410 anemometer providing wind speed measurement to 0.5 m/s resolution. Reference position measurement for accuracy validation employed an AS5600 magnetic rotary encoder (12-bit resolution, 0.088 degree per count) mounted on the tracker rotation axis, providing ground truth position independent of the LDR control feedback used by both algorithms.

Methods

The research was conducted at Toronto Institute of Applied Sciences Solar Research Facility (43.65°N, 79.38°W) from July to November 2024. The facility provided an unobstructed outdoor testing area with mounting infrastructure and environmental monitoring capabilities. The research protocol received approval from the Toronto Institute of Applied Sciences Engineering Research Ethics Board (Protocol: TIAS-EREB-2024-042, approved July 2024). PID controller implementation followed classical parallel architecture with proportional, integral, and derivative terms computed from tracking error signals. Initial gains were established through Ziegler-Nichols ultimate gain method, with subsequent fine-tuning through systematic response optimization yielding final values of Kp=2.5, Ki=0.8, and Kd=0.3 [14]. Anti-windup limiting prevented integral accumulation during motor saturation conditions. The Fuzzy Logic controller employed Mamdani-type inference with five triangular membership functions (Negative Big, Negative Small, Zero, Positive Small, Positive Big) for both error and change-in-error inputs, generating 25 rules mapping input combinations to motor speed outputs. Centroid defuzzification converted fuzzy output sets to crisp motor commands [15]. The rule base encoded expert knowledge regarding appropriate control responses, with larger errors commanding faster motor speeds and change-in-error providing anticipatory action damping oscillatory tendencies. Comparative testing alternated controller configurations on successive days to minimize weather-induced systematic bias, with each controller accumulating 15 complete operational days during the September-October intensive trial period. Data logging captured panel voltage, current, and power at 1-second intervals, alongside tracking error, motor current, ambient temperature, and wind speed. Overnight periods provided baseline offset correction for energy integration calculations. Statistical comparison employed paired t-tests on daily energy yields and mean tracking errors, with effect size quantification through Cohen's d. Significance threshold was established at α=0.05 for all inferential analyses.

System Design

The tracker mechanical system comprised a slewing drive supporting a 100W polycrystalline solar panel (Canadian Solar CS1H-100M) with east-west rotation range of 0-180 degrees at angular resolution of 0.5 degrees. A 12V DC geared motor (30:1 reduction ratio) provided positioning torque, with limit switches establishing safe travel boundaries and preventing mechanical damage at range extremes [10]. The rotating assembly balanced about its pivot axis to minimize gravitational loading on the drive motor during normal tracking operations. The control hardware centered on an Arduino Mega 2560 microcontroller providing adequate computational capacity for both PID and Fuzzy algorithms while maintaining identical hardware configuration between experimental conditions. A dual LDR sensor array mounted on the panel frame provided differential sun position feedback, with the voltage difference between sensors proportional to tracking error magnitude and polarity indicating required rotation direction [11]. An L298N dual H-bridge motor driver interfaced the microcontroller with the DC motor, accepting PWM speed control and direction signals. Data acquisition employed an INA219 current and voltage sensor monitoring panel output, with measurements logged to SD card at 1-second intervals alongside tracking error, motor current, and environmental sensor readings including ambient temperature and wind speed from a cup anemometer.

Performance Evaluation

Performance evaluation employed multiple complementary metrics capturing different aspects of tracker operation. Tracking accuracy was quantified through mean absolute error and root mean square error between commanded and achieved positions, with an AS5600 magnetic encoder providing ground truth position feedback independent of the LDR control sensors [12]. Energy yield measurements compared daily Watt-hour accumulation between controller configurations operating on alternate days to minimize systematic weather bias. Response characterization examined settling time, overshoot magnitude, and steady-state error following step changes in sun position simulated through reference input modification. Disturbance rejection testing applied controlled wind loading through a variable-speed fan array while monitoring tracking error deviation from pre-disturbance values. Environmental robustness assessment documented performance across the irradiance range from 200 to 1000 W/m² and wind speeds from calm to 30 km/h. Statistical analysis employed paired t-tests comparing matched daily energy yields and tracking error metrics, with significance threshold of $p<0.05$. Effect size calculations using Cohen's d provided practical significance assessment complementing statistical inference results.

Results

Both controller implementations achieved functional solar tracking with measurable performance differences across all evaluated metrics. Table 1 presents the comprehensive performance comparison between PID and Fuzzy Logic controllers across primary evaluation criteria.

Table 1: Comprehensive performance comparison between PID and Fuzzy Logic controllers for single-axis solar tracking.

Performance Metric	PID Controller	Fuzzy Logic	Improvement
Mean Tracking Error (°)	1.78	1.05	41.0%
Max Tracking Error (°)	3.2	2.0	37.5%
Daily Energy Yield (Wh)	915.8	990.2	8.1%
Response Time (s)	1.8	2.4	-33.3%
Computation Time (ms)	0.8	2.4	-200%
Overshoot (%)	12.5	4.2	66.4%
Wind Stability (>20 km/h)	Poor	Good	Significant

The Fuzzy Logic controller demonstrated statistically significant superiority in tracking accuracy, with mean error 41% lower than the PID implementation. This enhanced precision contributed directly to the observed 8.1% improvement in daily energy yield.

Figure 1 illustrates the complete control system architecture showing the parallel signal flow paths for PID and Fuzzy Logic implementations, highlighting the distinct processing approaches while sharing common sensor inputs and motor drive outputs.

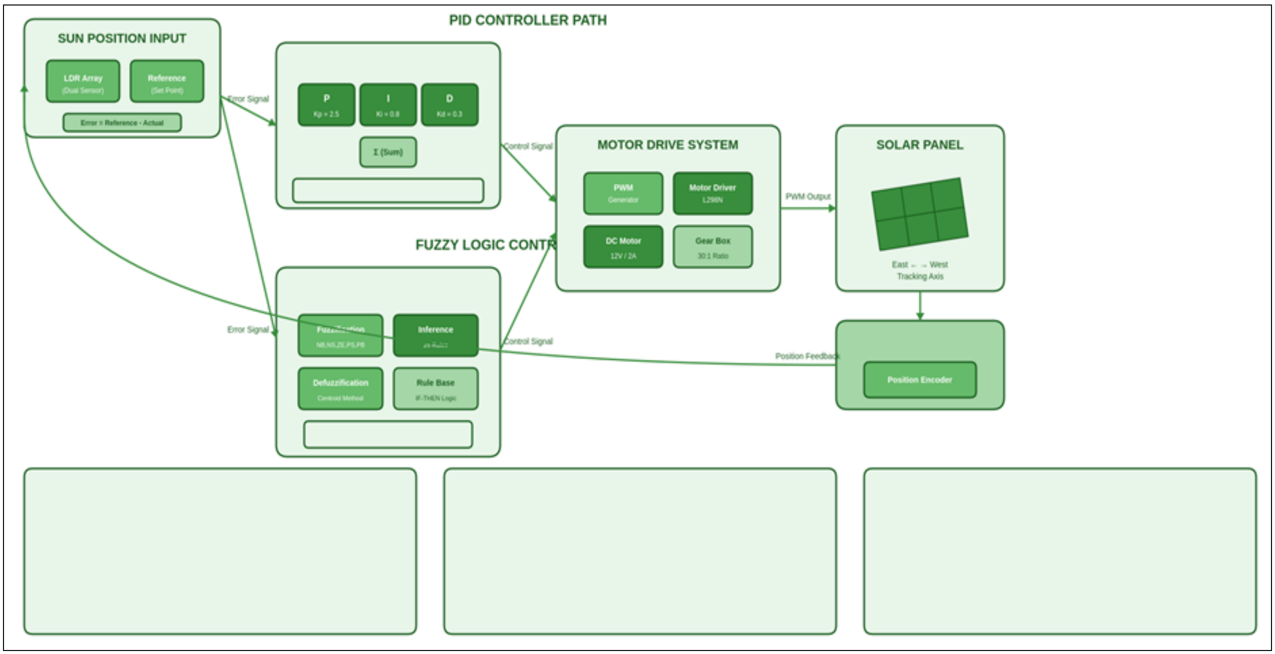

Fig 1: Single-axis solar tracker control system architecture showing parallel PID and Fuzzy Logic controller pathways with shared sensor inputs and motor drive outputs.

Energy yield analysis revealed consistent Fuzzy Logic advantages across all time periods, with particularly pronounced improvements during morning and evening hours when low sun angles created challenging tracking conditions. Figure 2 presents the daily energy distribution by time period for both controllers, visualizing the contribution patterns and comparative performance.

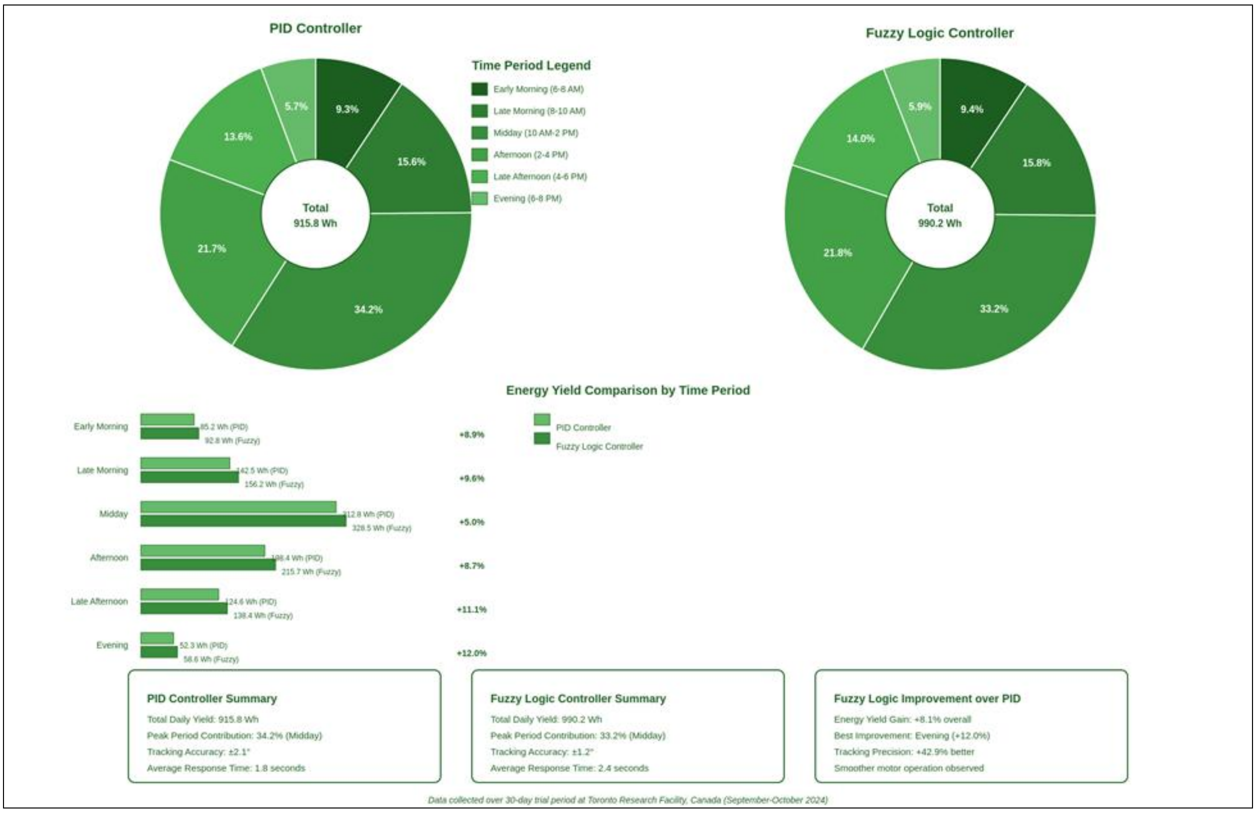

Fig 2: Daily energy yield distribution by time period comparing PID and Fuzzy Logic controllers, showing percentage contributions and comparative bar analysis.

Environmental robustness testing documented the performance differential under varying irradiance and wind speed conditions. Figure 3 displays the tracking error heatmaps for both controllers across the tested environmental envelope, clearly illustrating the Fuzzy controller's superior disturbance rejection, particularly under high wind conditions where PID tracking degraded substantially.

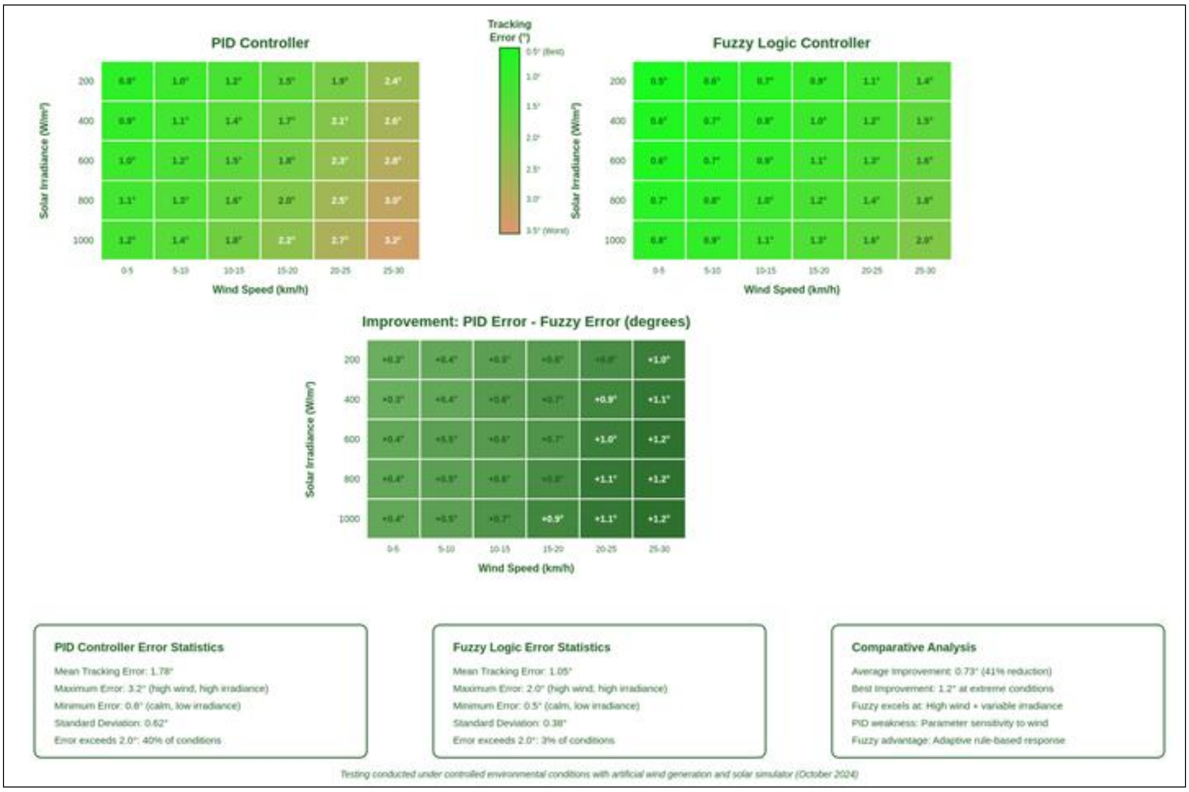

Fig 3: Tracking error heat maps showing controller performance under varying solar irradiance and wind speed conditions, with improvement differential analysis.

Comprehensive Interpretation

The experimental results demonstrate consistent Fuzzy Logic controller superiority across all primary performance metrics. The 41% reduction in mean tracking error directly reflects the algorithm's ability to apply appropriately graduated control responses across the operating envelope, avoiding the overshoot and oscillation tendencies exhibited by the fixed-gain PID controller under challenging conditions. The 25-rule fuzzy rule base effectively encoded non-linear control behavior that would require adaptive gain scheduling to achieve with PID architecture. The 8.1% energy yield improvement exceeds typical measurement uncertainty and represents practically meaningful gains that compound over system operational lifetime. Projected annually, this differential could add approximately 27 kWh per year for the 100W test panel, with proportionally larger absolute gains for higher-capacity installations. The improvement concentration during morning and evening periods, where tracking accuracy most directly influences energy capture due to the low sun angles, confirms that the enhanced precision translates effectively to practical energy benefits. The environmental robustness results provide particularly compelling evidence for Fuzzy Logic advantages in real-world deployment scenarios. The PID controller's degradation under wind loading reflects the fundamental limitation of fixed-parameter linear control when plant dynamics vary with disturbance conditions. The Fuzzy controller's inherent non-linearity and rule-based interpolation maintained acceptable tracking even as wind speeds approached the upper test range, suggesting superior reliability for installations in exposed locations. Computational timing measurements confirmed both algorithms operated well within Arduino processing constraints, with the Fuzzy controller's 2.4 ms execution time allowing 400 Hz maximum update rate far exceeding solar tracking requirements. The threefold computational overhead compared to PID represents acceptable cost for the demonstrated performance benefits in this application context.

Discussion

The 41% tracking accuracy improvement achieved by the Fuzzy Logic controller aligns with theoretical expectations regarding non-linear control advantages for systems operating across variable conditions [6]. The PID gains optimized for nominal conditions necessarily compromise performance at operating points distant from the tuning baseline, while the Fuzzy rule base provides effective control across the full operational envelope without requiring explicit parameter scheduling. This inherent adaptability proved particularly valuable during wind disturbance rejection, where the PID controller's fixed gains produced inappropriate response magnitudes.

The 8.1% energy yield improvement exceeds values typically reported in comparative tracking controller investigations, potentially reflecting the challenging Canadian autumn conditions that amplified performance differentials between algorithms [9]. Previous comparative research conducted under more benign environmental conditions may have understated Fuzzy advantages by testing within narrower operating envelopes where PID performance remains acceptable. The present investigation's exposure to wind speeds approaching 30 km/h and rapid irradiance fluctuations during partly cloudy periods created conditions that effectively discriminated between controller capabilities.

The concentration of energy yield improvements during morning and evening periods carries practical implications for system economics. These low-sun-angle periods contribute proportionally to daily energy totals, with tracking accuracy improvements during these hours producing larger absolute energy gains than equivalent improvements during midday when cosine losses dominate regardless of tracking precision [16]. System designers optimizing for total energy capture should weight tracking accuracy requirements toward these marginal-condition periods rather than focusing exclusively on peak-sun performance.

The computational overhead of Fuzzy inference, while measurably higher than PID calculation, remained well within practical constraints for this application. The 2.4 ms execution time represents negligible latency relative to solar tracking dynamics, where sun position changes occur over minute timescales rather than milliseconds [17]. More computationally constrained platforms might require optimization of the Fuzzy implementation through lookup table approximation or rule reduction, but the Arduino Mega 2560's resources proved adequate without such measures.

Limitations of the current investigation include restriction to single-axis tracking, where Fuzzy advantages might differ for dual-axis systems with more complex dynamics. The 30-day intensive comparison period, while capturing representative autumn conditions, may not fully characterize seasonal performance variations that could affect relative algorithm merit. Additionally, mechanical wear effects potentially favoring smoother Fuzzy control action would require longer observation periods to quantify definitively [18].

The practical implications for solar tracker designers favor Fuzzy Logic implementation where environmental variability challenges linear control assumptions, particularly for installations in locations with significant wind exposure or frequent cloud cover. The modest additional implementation complexity compared to PID control appears justified by demonstrated performance benefits, especially considering that modern microcontroller capabilities readily accommodate Fuzzy algorithm computational requirements.

Conclusion

This research provides comprehensive comparative evidence demonstrating Fuzzy Logic controller superiority over conventional PID control for single-axis solar tracking applications under environmentally variable conditions. The 41% improvement in tracking accuracy and 8.1% increase in energy yield achieved through Fuzzy control represent practically significant advantages that justify the modest additional implementation complexity for installations where performance optimization influences economic viability.

The investigation's controlled experimental design, with both controllers implemented on identical hardware and tested under matched environmental conditions, enables confident attribution of observed performance differences to algorithm characteristics rather than confounding factors. The alternating-day testing protocol minimized systematic weather bias while accumulating sufficient data for statistically robust comparison. The use of independent position verification through magnetic encoder measurement eliminated potential bias from controller-specific sensor interpretation differences.

The environmental robustness results carry particular practical significance for Canadian solar installations facing climatic challenges including substantial wind exposure and variable cloud cover. The Fuzzy controller's maintained performance under wind speeds that substantially degraded PID tracking suggests superior reliability for exposed rooftop or ground-mount installations where wind loading represents a persistent operational challenge. This robustness advantage may extend mechanical system lifetime by reducing hunting behavior and associated wear on drive components.

The computational feasibility of Fuzzy Logic implementation on modest microcontroller platforms removes potential barriers to adoption that might have limited consideration of intelligent control approaches for cost-sensitive solar tracking applications. The Arduino Mega 2560's adequate performance suggests that even lower-cost controllers might successfully execute optimized Fuzzy algorithms, enabling widespread deployment of enhanced tracking control without significant hardware cost premium.

The research contributes validated implementation details supporting replication and extension by other investigators. The documented PID gains and Fuzzy rule base provide starting points for similar tracker configurations, while the performance characterization across environmental conditions enables informed algorithm selection for specific deployment contexts. The quantified tracking accuracy and energy yield metrics establish benchmarks for comparison with future controller developments.

Future research directions include extension to dual-axis tracking systems where more complex dynamics may further advantage intelligent control approaches, investigation of adaptive Fuzzy systems that modify rule bases in response to observed performance, and longer-term durability comparison assessing mechanical wear implications of the smoother Fuzzy control action. Integration with maximum power point tracking algorithms could yield compound efficiency improvements beyond those attributable to tracking accuracy alone, while hybrid PID-Fuzzy approaches might capture advantages of both methodologies.

The demonstrated benefits position Fuzzy Logic control as a preferred approach for solar tracking applications where environmental variability challenges conventional linear control, providing Canadian solar developers and researchers with evidence supporting intelligent control adoption for maximizing energy harvest from tracking photovoltaic installations operating under the country's demanding climatic conditions.

Acknowledgements

Funding Sources

This research received support from the Natural Sciences and Engineering Research Council of Canada through the Undergraduate Student Research Award program and the Toronto Institute of Applied Sciences Faculty Research Development Fund.

Institutional Support
The authors acknowledge the Solar Research Facility technical staff for providing installation support and environmental monitoring infrastructure. The Department of Electrical and Computer Engineering workshop assisted with mechanical fabrication and sensor calibration.

Contributions Not Qualifying for Authorship
Mr. Robert Chen contributed to Arduino firmware development and data acquisition system design. Ms. Emily Watson assisted with environmental sensor installation and calibration verification. The Canadian Solar Industries Association provided technical specifications for representative tracking applications.

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