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HYBRID FUZZY–PID CONTROL FOR VARIABLE-RATE CENTER PIVOT IRRIGATION: AN AUTOMATION-DRIVEN APPROACH TO PRECISION WATER MANAGEMENT

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Abstract.

Precision agriculture increasingly relies on advanced automation and intelligent control strategies to address the spatial and temporal variability of crop water requirements while minimizing resource consumption. Center pivot irrigation systems are widely deployed in large-scale farming operations; however, their conventional control architectures are typically based on fixed schedules or linear feedback laws, which are insufficient to handle the nonlinear dynamics, uncertainties, and disturbances inherent in soil–plant–atmosphere interactions. This work presents the development and experimental validation of a hybrid Fuzzy–PID digital control system for variable-rate irrigation, designed to enhance automation, water-use efficiency, and operational performance in center pivot irrigation systems.

The proposed system integrates two coordinated control loops: one governing irrigation water dosage through real-time flow regulation, and a second controlling the angular positioning of the center pivot to enable spatially differentiated irrigation. The control architecture combines the robustness of classical PID control with the adaptability of fuzzy logic, allowing dynamic tuning of control actions in response to nonlinearities, parameter variations, and external disturbances commonly encountered in irrigation processes. This hybrid strategy is particularly well suited for precision water management applications, where system behavior is highly variable and difficult to model accurately.

A scaled experimental platform was implemented using low-cost, commercially available components. Soil moisture variability was emulated using a TCS34725 color sensor, while pivot motion and rotational speed were monitored through HC-020K encoder modules and B83609 velocity sensors. Actuation was achieved via a DC submersible mini-pump for variable water flow *control and a DC servomotor for pivot displacement, both driven by pulse-width modulation signals. The entire control system was deployed on an ESP32 microcontroller, enabling embedded real-time operation. Wireless monitoring and data visualization were implemented using LoRa™ communication, facilitating remote supervision and supporting digital farming workflows.*

Experimental results demonstrate excellent dynamic performance, with response times below one second and zero steady-state error achieved within 1.5 seconds for both water flow and angular position control. These results confirm the effectiveness of the hybrid Fuzzy–PID approach in compensating for system nonlinearities and maintaining desired irrigation targets. The proposed solution illustrates the synergy between agricultural automation and variable-rate irrigation, offering a scalable, energy-efficient, and cost-effective pathway toward smarter water management. This work contributes to the advancement of robotic and automated irrigation systems capable of improving water productivity, reducing energy consumption, and enhancing the economic sustainability of digital agriculture.

Keywords.
Agricultural Robotics; Center Pivot Automation; Fuzzy-PID Control; Precision Water Management; Variable-Rate Irrigation.

Introduction

The efficient management of water in agriculture represents one of the main global challenges, given the increasing demand for food, the limited availability of water resources, and climate changes affecting resource distribution. In this context, optimizing water use through precision irrigation technologies has emerged as a fundamental strategy to ensure agricultural sustainability (Kamienski, et al., 2019; Abioye, et al., 2022; Gupta, et al., 2025). The necessity of optimizing water usage, especially in water-scarce regions, has led to the integration of advanced control technologies with vision sensors and electronic actuators. This integration allows for the real-time regulation of water supply based on the specific conditions of each plot (Monteleone, et al., 2020; Janai & Jekabumar, 2019; Vijay, et al., 2023; Salimath, et al., 2023). Among these technologies, center-pivot and lateral-move irrigation systems have been widely adopted for their capacity to cover extensive areas with automated control, facilitating uniform and scheduled water application (Mohammed, et al., 2023; Ibrahim, et al., 2025; Saraiva, et al., 2020; Sapkota, et al., 2024; Cai, et al., 2022; Al-Agele, et al., 2022).

However, the implementation of controllers capable of managing the spatial and temporal variations of hydraulic demand in real-time still presents limitations. This is primarily due to the existence of multiple variables affecting the uniformity and efficiency of the applied water, such as variations in topography, soil properties, atmospheric conditions, and the inherent difficulty in modeling and managing uncertainty in agricultural environments (Li, et al, 2020; Al-Ghobari & Dewidar, 2021; Black, 2012).

Diverse approaches in the literature have addressed automatic control in irrigation systems to enhance resource efficiency. Traditional methods, such as PID controllers, have been used to regulate variables like water flow and pivot position, showing positive results in terms of stability and rapid response (He, et al., 2023; Jain, 2022). Nevertheless, these conventional PID-based strategies, while widely adopted for their simplicity and robustness, exhibit limitations when facing the inherent nonlinear conditions and disturbances of these processes, such as changes in crop water demand or variations in water availability.

In response, intelligent control techniques and hybrid control systems combining classic and modern control methodologies have been proposed as an effective alternative, given their ability to manage imprecise data and provide flexible, adaptive decisions (Nahar, 2019; Morchid, et al., 2025; Bazrafkan, et al., 2025; Song, et al., 2024; Marinescu, et al., 2017). Fuzzy control, in particular, has gained interest in agricultural applications due to its capability to incorporate heuristic and sensory knowledge into automatic decision-making.

Recent research has demonstrated that fuzzy control systems can improve water supply precision by dynamically adjusting irrigation doses based on variables such as the Normalized Difference Vegetation Index (NDVI), surface temperature, soil moisture, and other parameters obtained via remote sensing (Begovich, et al., 2007; Poyen, et al., 2023; Mendes, et al., 2024; Ma & Zhang, 2022; Khatri, 2018; Neugebauer, et al., 2023). These variables, combined with vision and remote sensing methodologies, offer a comprehensive view of crop status and enable resource management better tailored to actual plantation needs, thereby reducing waste and optimizing yields.

The combination of different control strategies, particularly the integration of PID and fuzzy control in a hybrid scheme, has been proposed as a promising solution to enhance the robustness, adaptability, and precision of smart irrigation systems. Hybrid controllers leverage the advantages of both classical and fuzzy control to efficiently manage the complex, nonlinear process variables typical of agricultural environments, achieving a more stable and adaptive response against environmental uncertainties.

Advancements in vision and remote sensing technology, particularly satellite imagery and in-field vision sensors, facilitate obtaining spatial and temporal information on crop status, including vegetation vigor indices and surface moisture. Integrating this data into a hybrid control system allows for a differential and optimized response tailored to the specific conditions of each field sector. In this context, the present study focused on the design and implementation of a hybrid digital control system that combines fuzzy control algorithms with PID control for the automatic and site-specific regulation of water flow and the angular position of a center-pivot irrigation system.

The objective is to improve water use efficiency and system operation by minimizing losses due to evaporation, runoff, and over-irrigation, in addition to reducing operational costs. This work provides a significant contribution to the field of automation and control in precision irrigation systems by offering a robust solution that integrates intelligent algorithms with classical control in a unified and scalable scheme.

Matherials and Methods

The configuration of the PID-Fuzzy hybrid control system for the automation of variable-rate irrigation in a center-pivot prototype integrates a data acquisition and processing platform based on an ESP32® microcontroller, perception sensors, PWM-controlled actuators, and LoRa™ wireless communication for remote supervision and variable visualization. The development was structured based on a modular architecture, employing readily available electronic technologies to ensure system reliability, precision, and reproducibility in diverse agricultural contexts.

System Architecture

The proposed system is structured into four main blocks: (a) Sensing and Perception Subsystem, (b) Processing and Control Subsystem, (c) Actuation Subsystem for regulating the central pivot's angular position and irrigation water flow, and (d) Remote Communication and Monitoring Subsystem. The overall architecture is illustrated in Fig. 1, which schematizes the interaction between perception elements, the hybrid control core within the ESP32® microcontroller, the actuators, and communication with the Graphical User Interface (GUI) via LoRa™.

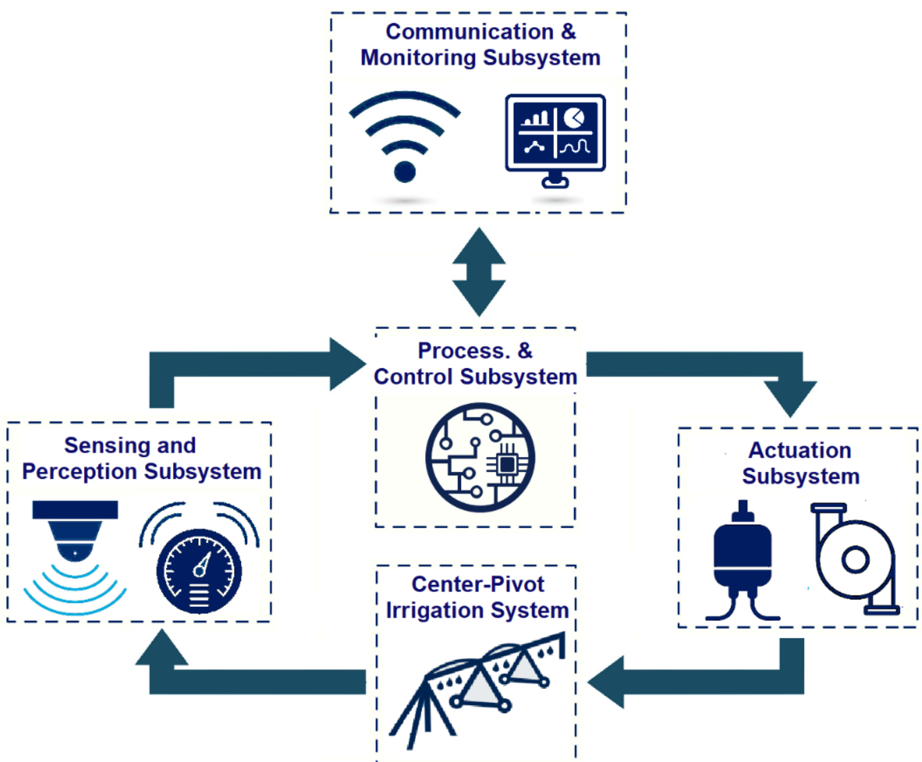

Fig 1. Structure of the Center-Pivot Digital Irrigation Control System.

Sensing and Perception Subsystem

For the perception of the central pivot system's process variables in the prototype, a TCS34725 color vision sensor was selected to emulate surface soil moisture using remote sensing. This sensor was chosen for its high-resolution and sensitive capability to detect color variations based on changes in reflectance levels, enabling a rapid and precise response to site-specific soil conditions. The sensor was installed along the central pivot arm to measure the crop foliage status at 30 cm. It was calibrated to measure red color (extreme water stress), yellow (moderate water stress), green (appropriate hydration status), and blue (soil oversaturation).

The sensor's accuracy was validated through controlled laboratory tests, confirming a measurement range between 0 and 255, with a resolution of 1 unit in the RGB value readings, recording a stable response to rapid reflectance variations directed to the Digital Control Subsystem. For measuring the pivot's angular velocity, B83609 sensors were employed in conjunction with HC-020K encoder modules, due to their high angular resolution and reliability.

This optical encoder measures the pivot's rotation speed, being coupled directly to the pivot's rotation axis, ensuring a rotational measurement proportional to the system's angular advance. The sensor was configured with an operating range to cover pivot displacement speeds in the experimental prototype between 0.5 rpm and 5 rpm, corresponding to slow-to-high velocity readings. The encoder signal was conditioned via PWM pulse reading on the ESP32® platform of the control subsystem, with a position measurement resolution of 0.1°.

Actuation Subsystem

Energy input to the central pivot system was implemented using a DC servomotor controlled by PWM for the pivot’s angular displacement (conditioned at ±12 with an H-Bridge - L298N). The servomotor's torque is 1.2 Nm, which is sufficient to move the pivot structure, offering a rotation range from 0° to 360°, performing a cyclic sweep in one rotation direction across the crop and then returning to its initial position. The servomotor's response was adjusted for a positioning accuracy of ± 0.5°. For water dosage (hydraulic dosing) in the crop area, a submersible DC mini-pump (conditioned at 12 VDC with an H-Bridge - L298N) was utilized, also regulated via PWM, which supplies water proportionally to the demand detected by the humidity sensor, within a range of 0 to 6 L/min. Both actuators are supplied by independent direct current sources, ensuring isolation and operational stability.

Processing and Control Subsystem

Two types of controllers were designed and synthesized on the ESP32® platform: a classic PID controller for the pivot’s angular velocity control loop, and a Hybrid PID-Fuzzy controller for the proportional water dosing control loop to the crop. The transfer functions for both control loops were obtained, and the controllers were designed considering the static and dynamic characteristics of the systems, including their gain matrix, response times, and steady-state error. Fig. 2 illustrates the connectivity of the different components of the center-pivot irrigation system to the processing and control subsystem.

The ESP32® board was selected because it possesses sufficient processing capacity to simultaneously manage both control loops. The implementation was carried out in C++, utilizing the Arduino and FreeRTOS frameworks for real-time task management. Furthermore, the ESP32® is compatible with the modules of the Sensing and Perception Subsystem (I2C communication port and Digital Input Pulse Port), the drivers of the Actuation Subsystem (Digital PWM Output Ports), and the Remote Communication and Monitoring Subsystem (SPI Port for the LoRa™ Ra-02 SX1278 Module).

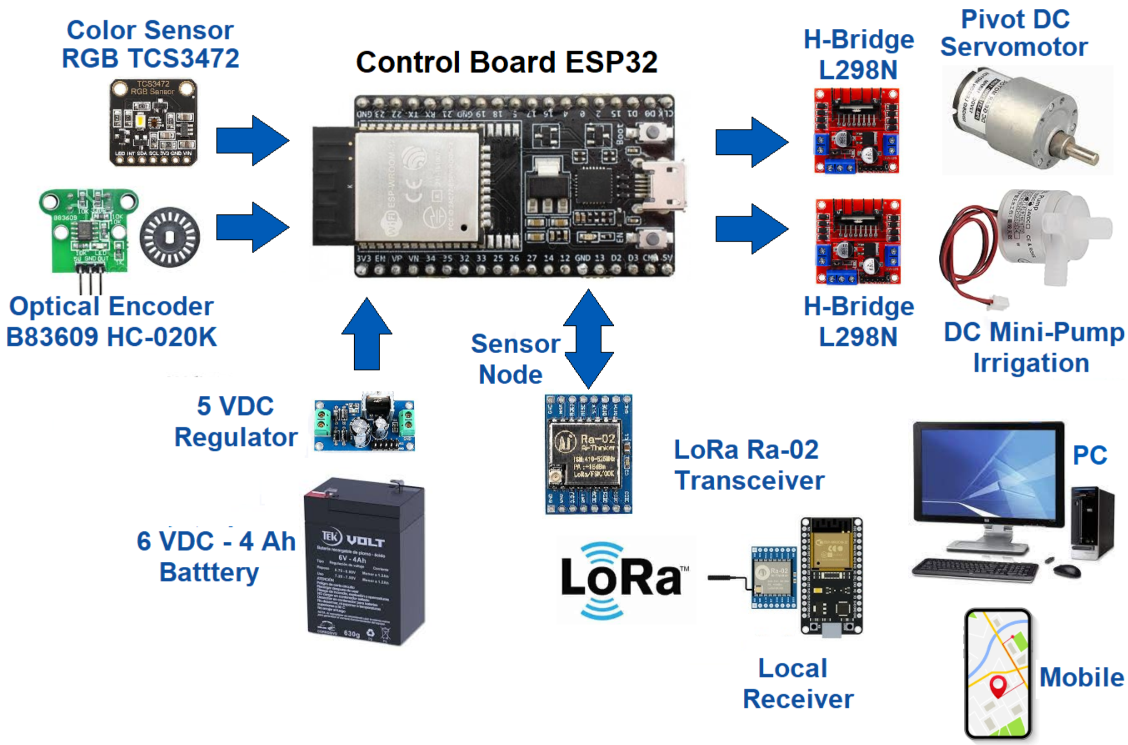

Fig 2. Components connected to the Processing and Control Subsystem of the Center-Pivot Irrigation System.

Remote Communication and Monitoring Subsystem

Wireless communication was configured using LoRa™ modules, enabling bidirectional data transmission of control and status information with low latency and reduced energy consumption. The Ra-02 transceiver module communicates with the ESP32® via the SPI (Serial Peripheral Interface) protocol at a frequency of 433 MHz, acting as a sensor node. It transmits the current status of the angular velocity references and outputs of the pivot and the soil hydration status.

The Ra-02 (SX1278) sends data directly to another transceiver connected to the PC/cell phone, which acts as a visualization and monitoring device, following an information flow: Sensor Node (ESP32-1 + Ra-02) → Local Receiver (ESP32-2 + Ra-02) → (USB/Serial or Bluetooth → PC/Cell Phone). Finally, the user accesses the dashboard from the PC or cell phone via a browser or application, visualizing the variables in real-time. The power supply for the electronic components comprising the center-pivot irrigation control system was integrated using a 6 VDC, 4 Ah battery, connected to a 5 VDC voltage regulator circuit.

Controller Design and Synthesis

Design of the PID Controller for the Center-Pivot Angular Velocity Control Loop

The transfer function of the pivot's angular motion system, driven by the DC servomotor, which relates the output angular velocity (ω_0) to the input PWM voltage (V_{PWM}) applied to the servomotor, was experimentally identified from data recorded through the instrumentation of this control loop. The pivot was ensured to be in an initial rest position of 0°. Subsequently, a constant input voltage (V_{PWM}, a PWM signal at 50% duty cycle) was applied to the DC servomotor in open-loop mode. This input corresponded to a step signal that displaced the pivot up to 360°.

The voltage applied to the servomotor was then reversed (with the same PWM) so that the pivot traveled cyclically from 360 back to the 0° reference position. Simultaneously with the input voltage recording, the response of the output angular velocity of the pivot (ω_0) was recorded as a function of time. The data for the DC servomotor input voltage and the conditioned output angular velocity, obtained from the encoder, were stored in the ESP32's serial plotter in a **.csv* file.

These data were directly transmitted to the Matlab® System Identification Toolbox (ident) as an *iddata* object with a sampling period of 0.05 seconds. Since the pivot's velocity response exhibited a stable overdamped dynamic behavior, the ident Toolbox was configured to estimate a first-order Transfer Function Model structured with one pole and a time delay. This resulted in the transfer function $G_V(s)$ (Eq. 1) with a model fit to the real behavior close to 91.5%.

$$G_V(s) = \frac{\omega_0(s)}{V_{PWM}(s)} = \frac{Ke^{-Ls}}{\tau s+1} = \frac{1.5e^{-0.2s}}{0.8s+1} \quad (1)$$

Once the transfer function for the center-pivot velocity control loop was obtained, a PID controller was designed through experimental tuning using the Matlab® PID Tuner tool. This tool relies on transient response optimization techniques, determining the optimal gain values by minimizing the accumulated error functions in pivot velocity regulation. The closed-loop dynamic specifications considered were: a stable, second-order underdamped response with a maximum overshoot less than 10%, a settling time less than 3 seconds, and a steady-state error less than 2%.

The PID controller was implemented with a sampling period T_s = 50 ms. At each instant, the error between the reference angular velocity (variable between 0.5 to 5 rpm) and the conditioned angular velocity measured by the encoder is calculated. The PID controller's output was used to generate the PWM signal that drives the servomotor, ensuring a variable speed according to the reference adjustment with precision and rapidity in the predefined irrigation zones. The recursive equation of the digitally implemented PID controller, with the digitized proportional, integral, and differential control gains, is described in Eq. (2), which was synthesized on the ESP32® board:

$$u[n] = K_p e[n] + K_i \sum_{j=0}^{n} T_s e[n] + K_d \frac{e[n]-e[n-1]}{T_s} \quad (2)$$

Where $u[n]$ is the control signal at instant n, $e[n]$ is the error (the difference between the velocity reference signal and the conditioned pivot velocity signal from the encoder), and K_p = 3.2, K_i = 8 and K_d = 0.16 are the proportional, integral, and differential control action gains, respectively, obtained through the tuning process.

Design of the Hybrid PID-Fuzzy Controller for the Water Dosing Control Loop

Similar to the pivot velocity control loop, the transfer function of the instrumented system was obtained via experimental identification. This function relates the output water flow (Q_0) for irrigation to the input PWM voltage (V_{PWM}) applied to the submersible DC mini-pump. The experimental procedure also utilized the Matlab® System Identification Toolbox (*ident*), beginning with the data logging of the PWM step input (V_{PWM}) applied to the mini-pump. This signal transitioned from the pump's inactive operating point to a constant PWM signal value of 70% duty cycle.

S Simultaneously, the output water flow measurement (Q_0), which oscillated between 0 L/min and 6 L/min, was recorded as a function of time. The data were captured in the ESP32's serial plotter and converted into a **.csv* file. This file was then adapted to an *iddata* input/output data format with a sampling period of 0.05 seconds to be imported into the Matlab® ident Toolbox. Since the output water flow response exhibited a stable first-order overdamped behavior, a transfer function GQ(s) was estimated with one pole and a transport delay. The fit between the obtained model and the actual experimental data was 89.2% as shown in Eq. (3).

$$G_Q(s) = \frac{Q_0(s)}{V_{PWM}(s)} = \frac{Ke^{-Ls}}{\tau s+1} = \frac{0.8e^{-0.05s}}{0.5s+1} \quad (3)$$

The Hybrid PID-Fuzzy controller for the water dosing control loop in the central pivot was designed using the Matlab® Fuzzy Logic Toolbox. The design was based on combining both control approaches: fuzzy control offers a good dynamic response, especially during transients and potential nonlinearities in the crop's soil moisture (color), but it inherently does not eliminate the steady-state error. Conversely, the PID controller excels at eliminating the system's steady-state error, achieving zero error, but often operates within a limited optimal range. The combination of both control approaches compensates for individual disadvantages, resulting in a Compound PID-Fuzzy controller whose structure is illustrated in Fig. 3.

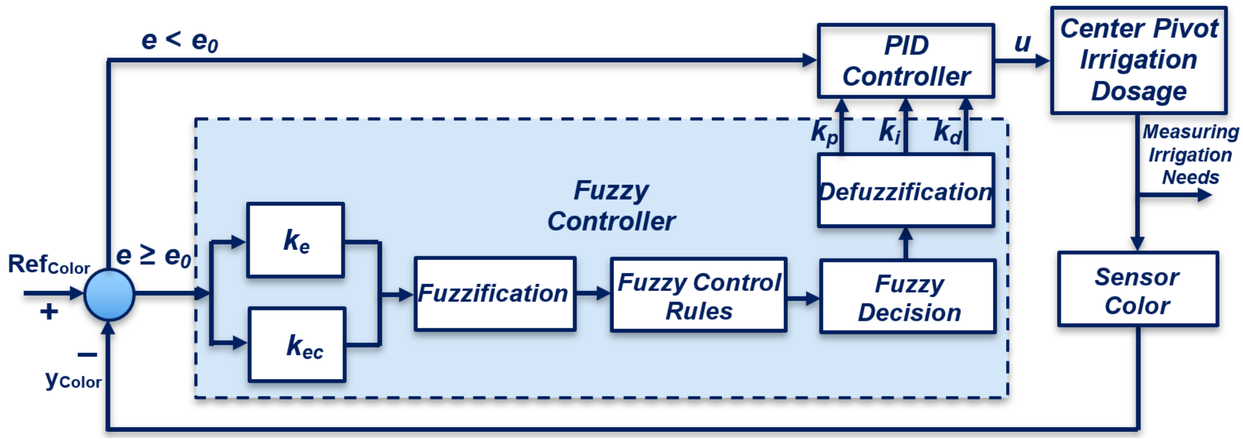

Fig 3. PID-Fuzzy Structure for the Irrigation Dosing Control Loop.

The difference between the crop color/humidity reference signal (Ref_{Color} and the output of the color sensor (humidity) (y_{Color}), which detects the level of water stress in the crop installed on the pivot, is used as the tracking error signal e ($e = Ref_{Color} - y_{Color}$). The hybrid control scheme operates under the following switching criterion: when the error $|e| < e_0$, the system is considered to be operating in a linear, steady-state region, and the PID controller is applied for irrigation dosing.

Conversely, if the error $|e| \geq e_0$, the system is considered to be operating in a nonlinear, transient response region, and the Fuzzy controller is engaged. This hybrid control scheme ensures that the center-pivot irrigation system maintains excellent dynamic performance and minimal steady-state error. The main advantage lies in the fuzzy system's capability for adaptive and online tuning of the PID controller's gains, overcoming the limitations of a conventional PID in the face of process nonlinearity.

The fuzzy controller utilizes two input variables: the humidity error (e) and the rate of change of humidity error ($e_c = de/dt$). The numerical values of e and e_c are subjected to the fuzzification process through the use of scaling (or quantization) factors k_e y k_{ec}, respectively. This initial step determines the degree of membership of the inputs to the predefined fuzzy sets.

The definition of the fuzzy input sets is based on the linguistic representation of the soil humidity (color) conditions. In this case, the universe of discourse for variables e and e_c is mapped from the TCS3472 sensor reading (used as an indirect indicator of soil moisture) across a quantitative range of 0 to 255. These input variables were categorized into four linguistic states of Soil Humidity (SH) and their respective fuzzy subsets: SH = {VDS, MS, MH, VS}.

Where VDS (Very Dry Soil) indicates a high water need (red/orange sensor reading); MS (Medium Dry Soil) represents that the land requires a moderate amount of water (ochre/yellow sensor reading); MH (Medium Moist Soil) reveals that the soil moisture level is below the appropriate point (greenish tone sensor reading); and finally VS (Very Saturated Soil), when the land has an adequate or saturated moisture level and requires no more water (blue tone sensor reading).

These states are associated with triangular and trapezoidal Membership Functions that define the degree of membership of a color tone reading to each category. The configuration of these functions, along with the output gains for the PID controller, was performed in the Matlab® Fuzzy Inference Editor, as illustrated in Fig. 4. The selected inference mechanism was Mamdani, and the defuzzification method used is the Centroid (or Center of Gravity of the Area).

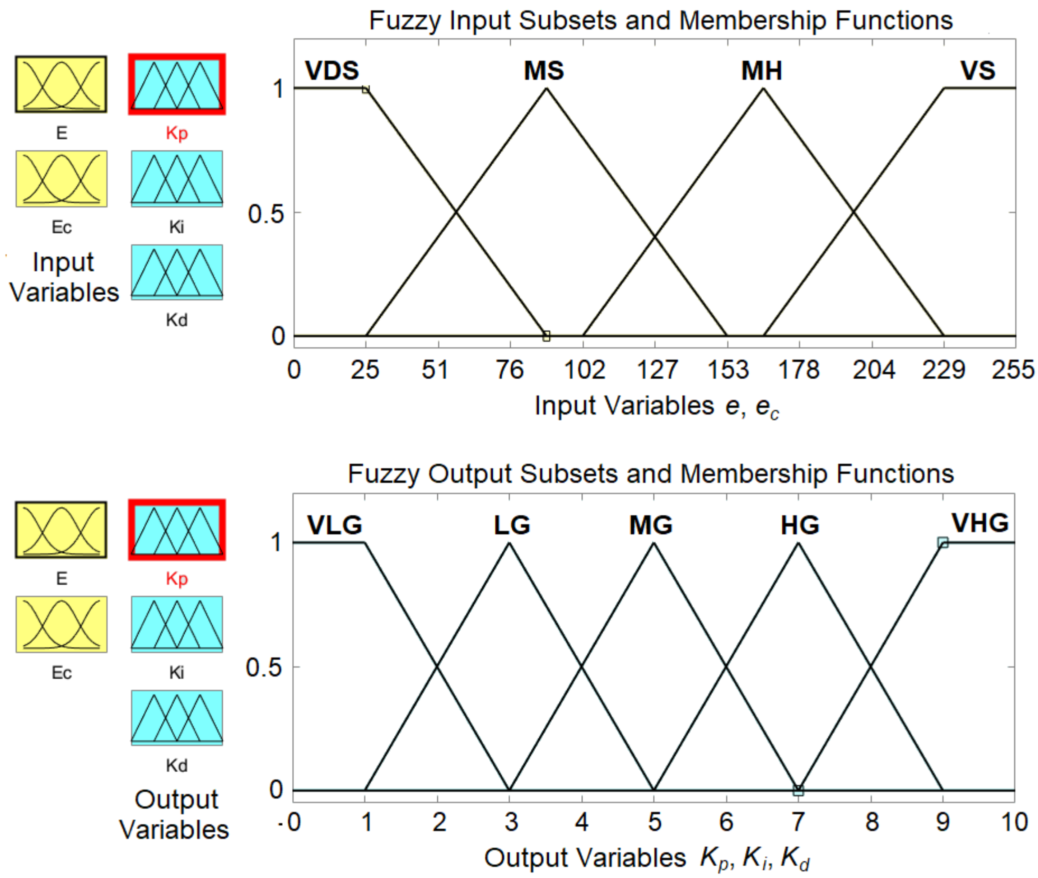

Fig 4. PID-Fuzzy Structure for the Irrigation Dosing Control Loop.

The output of the fuzzy control system consists of the adaptive tuning gains for the PID controller: the proportional gain K_p, the integral gain K_i, and the differential gain K_d. These gains update the general form of the PID synthesized in Equation (2) for the water supply control loop in the irrigation system.

The Output Fuzzy Set (GS) was defined by five linguistic states: GS = {VLG, LG, MG, HG, VHG}, which determine the intensity of correction to be applied. Here, VLG (Very Low Gain) corresponds to zero water supply (pivot inactivity); LG (Low Gain) means minimum liquid supply; MG (Medium Gain) is used for intermediate or normal water supply; HG (High Gain) corresponds to significant water supply; and finally, VHG (Very High Gain) is used when the maximum water flow is supplied.

The quantitative domains of the output gains were defined in the following ranges: 0 to 10 for K_i, 0 to 5 for K_p, and 0 to 0.5 for K_d. The fuzzy gains are *defuzzified* using their respective scaling factors to obtain the adjusted numerical values. Finally, the Digital PID Controller, equipped with these adapted gains, generates the control signal u, which is translated proportionally into the PWM signal (0 to 255) applied to the water supply mini-pump in the central pivot irrigation system.

The decision rule base was formulated based on the heuristic operating logic of the central pivot irrigation system, adapting to soil moisture conditions and providing the adequate water flow in each crop irrigation zone. The decision rules have the form: 'IF e AND e_c, THEN K_p, K_i AND K_d', resulting in a total of 4×4 = 16 conditional rules, synthesized in Table 1.

Table 1. Fuzzy Control Rules for Central Pivot Irrigation Control.

e \ e_c	VDS	MS	MH	VS
	K_p, K_i, K_d			
VDS	VHG, VHG, HG	VHG, VHG, HG	HG, HG, MG	HG, HG, MG
MS	HG, HG, MG	MG, MG, MG	MG, MG, LG	MG, MG, LG
MH	MG, MG, LG	LG, LG, LG	LG, LG, LG	LG, LG, VLG
VS	LG, LG, VLG	LG, LG, VLG	VLG, VLG, VLG	VLG, VLG, VLG

The behavior of the gains K_p, K_d and K_i as a function of the inputs e and e_c is visualized in the 3D control surfaces shown in Fig. 5, which confirm the adaptive control action. System validation was performed using Matlab®/Simulink™ simulations, verifying the robustness of the system's response against disturbances, changes in hydraulic demand, and variations in operating conditions. The final implementation of the Hybrid Digital PID-Fuzzy controller was synthesized on the ESP32® control platform.

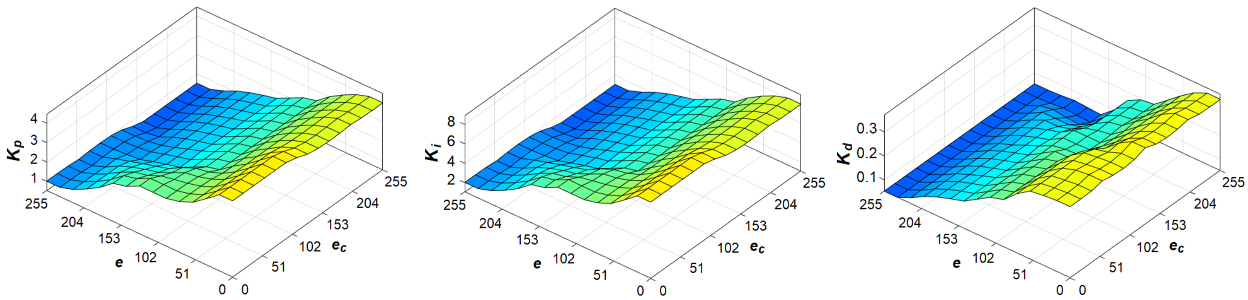

Fig 5. Surface Diagrams for the Hybrid PID-Fuzzy Controller Gains.

Results and Discussion

The experimental results derived from the design and implementation of the proposed digital control architecture—consisting of the PID velocity control for the pivot and the Hybrid PID-Fuzzy control for water dosing—demonstrated outstanding dynamic and static performance in the variable-rate center-pivot irrigation system prototype (Fig. 6), thereby validating the effectiveness of the implemented control strategies.

Fig 6. Implemented Scale Prototype of the Center-Pivot Irrigation System.

Performance of the Pivot Velocity Control Loop (PID Controller)

The PID controller implemented for the regulation of the central pivot's angular displacement exhibited dynamic and static performance consistent with the pre-established design specifications. Experimental step response tests, evaluated against angular velocity reference variations (2.5 rpm and 4.8 rpm), yielded an average settling time less than 4 seconds, as shown in Fig. 7:

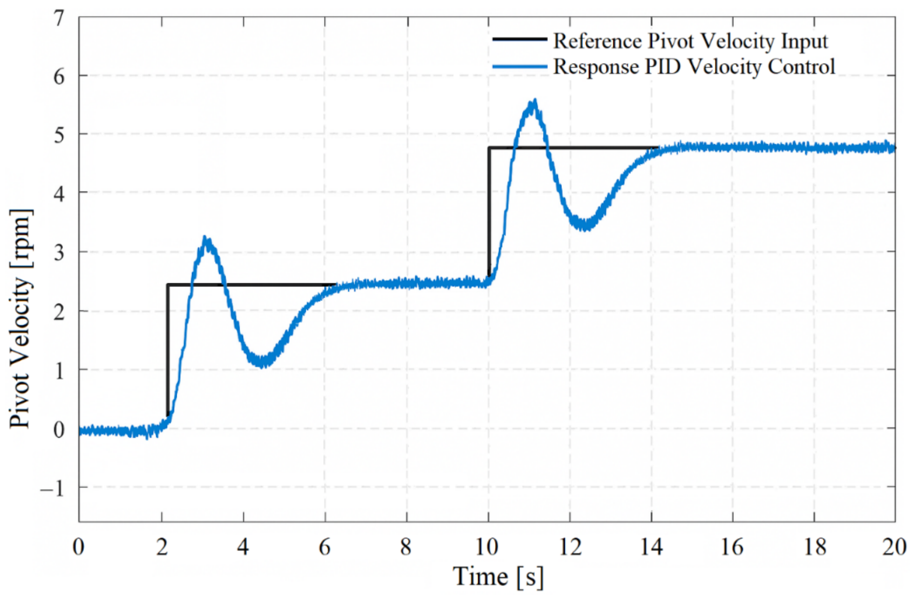

Fig 7. Experimental Response of the PID Control for Pivot Velocity in the Implemented Center-Pivot Irrigation System.

In all transient tests, the system achieved the desired angular velocity with a maximum overshoot less than 10%. This low overshoot indicates a robust tuning of the PID controller gains (K_p = 3.2, K_i =8.0, K_d =0.16), which favored a rapid, underdamped response. From the perspective of site-specific irrigation, this behavior translates into an agile pivot positioning capability, a fundamental factor for rapidly transitioning between zones with different water requirements.

Positioning precision was confirmed by a practically zero steady-state error, stabilizing completely in less than 4 seconds. This result ensures that each sector of the crop is exposed to irrigation accurately, without significant deviations that could compromise the uniformity of water application. The robustness of the feedback, provided by the encoder and the 20 Hz sampling frequency (sampling period T_s = 50 ms) of the ESP32®, contributed to achieving this precision.

Performance of the Water Dosing Control Loop (Hybrid PID-Fuzzy Controller)

The Hybrid PID-Fuzzy controller, focused on the adaptive management of the volumetric flow supplied by the mini-pump, demonstrated an exceptional capability to compensate for the nonlinearities inherent in fluid dynamics and the changing nature of the hydraulic requirement. The system's response to the various step flow references (1.5 L/min – 3.0 L/min – 4.5 L/min), defined by the emulation of soil moisture control via the color sensor, satisfied the established dynamic and static specifications, as evidenced in the PID-Fuzzy control response shown in Fig. 8.

An average response time less than 1 second was recorded for transitions between different flow levels, ensuring an almost instantaneous water dosage when the pivot moves between irrigation zones. The steady-state error for water flow tracking also converged to zero in approximately 1.2 seconds. This result underscores the high effectiveness of the Hybrid PID-Fuzzy controller in maintaining the desired flow.

Notably, the fuzzy logic managed to precisely map the heuristic conditions of "humidity" and "dryness" of the terrain into a PWM control signal for mini-pump activation, without requiring an exact mathematical model of the system's fluid dynamics, thus validating the knowledge-based approach. Additionally, the adaptability of the hybrid control was evident in its capacity to effectively counteract pressure variations originating from the storage tank and disturbances generated in the hose, guaranteeing a constant and precise water delivery at any point along the pivot's path.

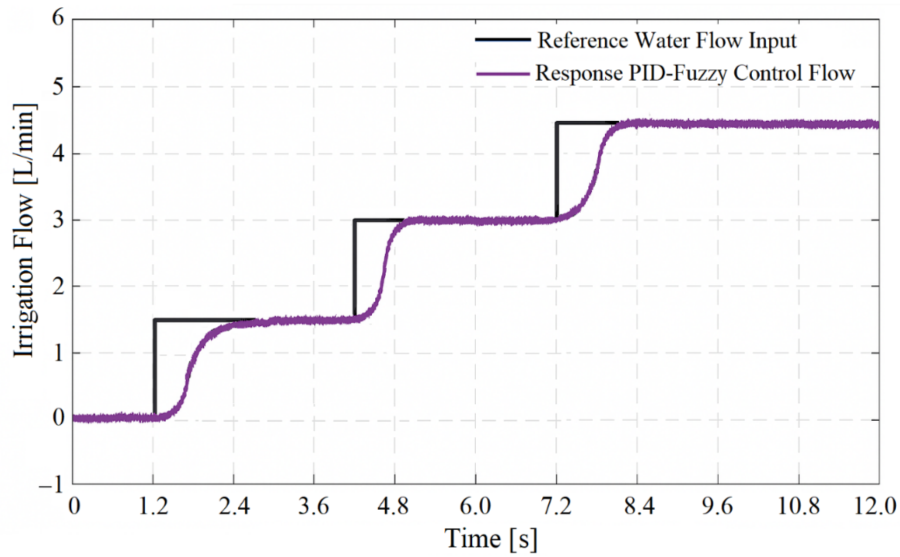

Fig 8. Experimental Response of the PID-Fuzzy Control for Water Flow Dosing in the Implemented Center-Pivot Irrigation System.

The integration of the PID and Fuzzy controllers into a hybrid control architecture proved to be a highly effective strategy. The conventional PID controller provided the robustness and the capability to eliminate steady-state error for supplied water flow regulation, while the Fuzzy control successfully managed adaptive tuning and nonlinear, variable hydraulic dosing.

This integration resulted in a closed-loop system with outstanding stability, demonstrated by the absence of sustained oscillations and a global response that was either overdamped or slightly underdamped but well-attenuated. Table 2 summarizes the comparison of the performance obtained for each controller, allowing for a quick interpretation of their respective advantages and the justification for their application in each control loop.

Table 2. Fuzzy Control Rules for Central Pivot Irrigation Control.

Evaluated Parameter	Velocity Control Loop (PID)	Dosing Control Loop (Hybrid PID-Fuzzy)	Comparative Advantage/Disadvantage
Controller	Conventional PID	Hybrid Switched PID-Fuzzy	Hybrid's superiority in nonlinear operating regions.
Controlled Variable	Pivot Angular Velocity (rpm}	Water Volumetric Flow (L/min)	----
Settling Time (t_s)	Less than 4.0 s	Less than 1.0 s (for flow)	PID-Fuzzy is faster in its loop (due to rapid adaptation, improving efficiency and precision).
Maximum Overshoot (%OS)	Less than 10%	Minimal / Practically zero (well-attenuated response)	PID-Fuzzy provides better transient attenuation. Stable and controlled response.
Steady-State Error (E_{ss})	Less than 1% Practically zero.	Less than 1% Practically zero.	Both meet the zero-error specification.
Robustness to Nonlinearity	Limited (fixed tuning)	High (Adaptive tuning via fuzzy logic)	Clear advantage for PID-Fuzzy in water management.
Agricultural Impact	Agile and precise positioning (site-specific irrigation).	Irrigation uniformity and water efficiency by ensuring exact flow rate.	----

The global steady-state error for the system was consistently less than 1%, a significant achievement that demonstrates the hybrid architecture's capacity to maintain the system operating close to the desired setpoints for pivot angular velocity and water flow supply to the crops.

To validate the controllers' accuracy, standard error metrics were calculated from the experimental data obtained during reference transitions. The estimated values reflect the high precision observed in the described results, which are reviewed in Table 3. Direct comparison of the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE) values between distinct loops (rpm vs. L/min) is limited. However, the Mean Absolute Percentage Error (MAPE) is a key, transversal metric that demonstrates the superiority of the Hybrid PID-Fuzzy control in terms of relative precision, achieving a mean absolute percentage error twice lower than the conventional PID controller.

Table 3. Error Metrics Applied to the Control Loops.

Control Loop	Control Strategy	MAE (Mean Absolute Error)	RMSE (Root Mean Square Error)	MAPE (Mean Absolute Percentage Error)
Angular Velocity (rpm)	Conventional PID	0.08 rpm	0.15 rpm	1.6 %
Water Dosage (L/min)	Hybrid PID-Fuzzy	0.015 L/min	0.035 L/min	0.8 %

The analysis of the error metrics and dynamic response for the PID pivot velocity control loop reveals that the magnitude of the MAE (0.08 rpm) is low, indicating high precision in tracking the desired pivot velocity trajectory. This error is concentrated almost exclusively during the transient regime (settling time). In the steady state, the error converges to zero rapidly (less than 4 s), which aligns with the inherent capacity of the PID's integral action to eliminate deviation.

The RMSE, being slightly higher than the MAE, suggests more significant error peaks during initial transients or overshoots. This indicates that the fixed tuning is sufficient and robust for the linear dynamics of pivot movement, ensuring fast and stable positioning. The error analysis for the Hybrid PID-Fuzzy water dosing controller showed a notably low MAE (0.015 L/min) and a MAPE of 0.8%, confirming that the steady-state error is consistently less than 1%, as verified by the results. The error exhibited rapid attenuation (response time less than 1 s).

The remaining error, although minimal, is better distributed thanks to the action of the fuzzy logic, which adapts the gains in response to changes in operating conditions (simulating soil moisture/color variations). This adaptive behavior minimizes oscillation and overshoot. The hybrid structure capitalizes on the best of both approaches: the speed and nonlinear robustness of Fuzzy control and the steady-state error elimination of the PID. This is fundamental in the water dosing loop, which is inherently more susceptible to disturbances and nonlinearities, thereby justifying the implementation of hybrid control.

Conclusion

The development and implementation of the Hybrid PID-Fuzzy digital control system for managing variable-rate irrigation in center-pivot systems demonstrated outstanding dynamic and static performance and high operational precision. The proposed control architecture validated its effectiveness by achieving response times less than 1 second and a practically zero steady-state error in both control loops: the PID for rapid angular pivot positioning and the Hybrid PID-Fuzzy for optimal, nonlinear water flow dosing. This speed and precision are crucial for site-specific irrigation.

The closed-loop stability and a global steady-state error consistently less than1% confirm the robustness of the hybrid strategy in counteracting disturbances and managing the uncertainties inherent in fluid systems and changing crop environment conditions. This work represents a significant contribution by coherently integrating the control of travel speed and water flow supply, promoting the optimization of vital liquid dosage in crops and enhancing the rational use of water resources.

The results validate the technical feasibility of this advanced approach for developing smart irrigation systems, although further testing in extended field scenarios is suggested to confirm its applicability in diverse agricultural environments.

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