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Research paper

Design and Implementation of An Intelligent Hoist Mechanism for Barrage & Dam Gate Operation

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Abstract

Water management relies on precise control of barrage gates to regulate irrigation, flood control, and hydropower. Traditional manual and simple electromechanical systems struggle with lag, unpredictable response, and energy waste under varying hydraulic loads. This paper designs an intelligent hoist mechanism integrating ultrasonic and pressure sensors with rotary encoders and a hybrid Proportional Integral Derivative (PID) fuzzy logic controller, simulates structural strength in ANSYS and control logic in MATLAB Simulink, and then implements Programmable Logic Controller (PLC) and Internet of Things (IoT) modules for real-time monitoring and adaptive actuation. A 4.5-meter height, 18.00 span gate weighing 30.75 tons responded smoothly, time response would vary, reaching 90% open in 608 seconds and full travel in 675 seconds. Under flows from 12.60 to 283.50 cubic meters per second, the gate opening ranged from 20 to 450 centimetres, with motor rotations from 490 to 8400 and speeds from 98 to 1500 RPM; power draw varied between 800 and 2200 watts. The proposed system delivers energy efficiency, stable operation, and scalable performance for dynamic water regulation.

Keywords: *Intelligent Hoist Mechanism; Barrage Gate Operation; Water Management; Proportional Integral Derivative; MATLAB; and ANSYS.*

1. Introduction

Water resource management is integral to modern infrastructure, particularly in areas that depend on dams, barrages, and sluice gates for irrigation, flood control, and hydropower generation [1], [2]. Regulation of water flow over rivers and canals is critical with barrage gates, and their smooth operation directly affects agricultural production, municipal water supply, and environmental equilibrium [3]. Traditionally, gate hoisting systems have been operated manually or through basic electromechanical systems [4]. However, with the rising need for responsive and sustainable water management systems, there is a growing shift toward intelligent, automated hoist systems capable of adjusting to dynamic water flow conditions and operational requirements [5-7].

The integration of Supervisory Control and Data Acquisition (SCADA) systems and Internet of Things (IoT) platforms has made real-time monitoring, as well as control of hydraulic structures, possible, allowing traditional water gates to become innovative systems [8,9]. These systems utilize sensors, actuators, and edge devices to gather and process data on water levels, gate position, vibration, and environmental conditions [10]. By integrating adaptive algorithms and automated control logic, innovative hoist mechanisms improve operational accuracy, safety, and power efficiency [11], [12].

Recent research highlights the potential of integrating machine learning, sensor fusion, and feedback control in enhancing the responsiveness and stability of hydraulic gate operation [13]. For example, studies on floodgate automation with real-time hydrodynamic modelling and predictive algorithms have indicated improvement in safety and flood mitigation performance [14], [15]. Furthermore, innovative technology like AI-assisted actuators and microcontroller-driven automatic systems effectively managed unstable water surges and gate resonance scenarios, enhancing structural durability [16], [17].

Beyond flood regulation, innovative gate systems enhance water use efficiency in irrigation and agricultural applications [18]. Several studies have developed an anticipatory valve control system for irrigation networks based on real-time weather and soil data [19]. The framework can be applied to barrage hoisting systems, where the hoist responds to water level and upstream and downstream demand projections, thus allowing anticipatory gate management [20]. Preliminary studies and field observations at the Ghaghara and Sharda barrages indicate limitations in their current operational models, such as inadequate integration of telemetry data and poor responsiveness to sudden inflow changes [21], [22].

The barrage gate system consists of a smart motorized hoist coupled with an array of water level sensors, vibration sensors, and programmable logic controllers (PLCs) [23], [24]. A master controller analyzes sensor signals and makes control decisions based on pre-programmed operating logic and adaptive thresholding [25]. The utilization of IoT modules ensures remote access and cloud-based analysis, enabling stakeholders to monitor gate status and operational metrics in real time [26]. Besides, this system is also meant to cater to prevalent issues in conventional hoist operations, such as latency during manual operations, inaccurate gate positioning, and unforeseen structural loading at high water discharge speeds [27]. Through automation of the hoist mechanism and incorporation of intelligent decision-making layers, the given system not only improves operational precision but also reduces human interference, enhancing safety and reliability [28], [29].

This study proposes bridging a fundamental barrage management gap by providing a low-cost, expandable, intelligent automation solution for hoisting mechanisms. This research aims to design and implement an intelligent hoist mechanism for barrage gate operation that ensures responsive, safe, and energy-efficient performance under dynamic hydraulic conditions. The objective is to overcome the limitations of conventional semi-automated systems by integrating sensing units, adaptive control logic, and robust actuation to enable precise gate movement and water flow regulation, especially during critical flood and irrigation events. The following are the significant contributions of the research:

- Developed an intelligent, sensor-driven hoisting system integrating ultrasonic, pressure, and rotary encoders with a hybrid PID + Fuzzy logic controller for adaptive gate control.
- Employed ANSYS for mechanical strength validation and MATLAB Simulink for control logic simulation to ensure structural safety and smooth gate operation.
- Proposed and implemented a PLC-Arduino-based hybrid control framework that dynamically tunes PID gains using fuzzy logic for robust response under fluctuating hydraulic loads.
- Demonstrated energy savings and minimized overshoot and steady-state error using a VFD-driven motor system optimized for water level and gate load conditions.

The following are the research questions of the research:

- How can machine learning models predict gate fatigue under extreme hydraulic or flood conditions?
- How can predictive analytics enhance the long-term reliability and safety of automated barrage gates?
- What are the optimal sensor configurations and data fusion strategies for multi-gate control systems in real-time operation?

2. Literature Review

In this section, various studies are reviewed and analyzed, and several authors have investigated and implemented them.

2.1. Intelligent hoist gate mechanism for barrage operations

A dual-stage advanced machine learning framework (EnsembleCNN) was proposed by Hosny et al. (2025) [30] for enhancing discharge coefficient (Cd) estimation of vertical sluice and radial gates in submerged flow conditions. Combining five ML models with a CNN-LSTM structure improved residual connections and an attention mechanism, making the model highly accurate with root mean square errors (RMSE) of 0.0552 and 0.0173, respectively. This innovative, mechanized solution surpassed manual methods, providing a strong and flexible solution for optimizing agricultural water resources. Building upon the need for reliable gate operation and maintenance, Duan et al. (2024) [31] created a split four-track cleaning robot for steel gates, tackling corrosion and biofouling caused by alternating wet-dry exposure. Performance tests confirmed stable operation at speeds >0.052 m/s with loads <5 kg and efficient removal of silt and shellfish, ensuring fitness for real-world applications. In parallel, Wang et al. (2024) [32] introduced a better gate-opening control system with a fuzzy PID controller optimized by an upgraded Beetle Antennae Search (BAS) algorithm for Direct Current (DC) motors. Simulation outcomes performed better than conventional BAS and particle swarm optimization methods, with improved convergence and reduced oscillations. Further refining hoisting mechanisms, Zang et al. (2022) [33] designed a nonlinear backstepping control method to reduce tension imbalance between two wire ropes in an electro-hydraulic hoisting system. Experiment results confirmed that the new TDO-CDO aided control method greatly enhances rope tension balance, providing smoother and more stable hoisting performance. Extending the safety dimension, Narimani et al. (2021) [34] examined air entrainment in the dam bottom outlet to reduce cavitation erosion, which is typical in hydraulic structures. The research experimentally evaluated six Iranian dams and simulated air aeration with three machine-learning algorithms. Findings emphasized that air aeration effectiveness depends on these two hydrodynamic variables, highlighting the model's value in dam safety management.

2.2. Barrage gate mechanisms & control systems

Expanding on flood mitigation efforts, Rathnayaka et al. (2024) [35] suggested a more efficient flap gate system for flood control in the Malwathu Oya River (Sri Lanka) along the Halpan Ela Anicut. Flow simulations indicated a 9 kPa (0.9 m water head) pressure drop over the current gate system at 1740 m^3/s flow, with upstream pressures decreasing from 114,492.5 Pa to 105,406 Pa. While the system costs USD 0.1 million, it can reduce annual flood damage to more than USD 0.2 million, making it a cost-efficient flood mitigation measure for Anuradhapura City. Addressing system control under complex operational scenarios, Bessa et al. (2022) [36] presented an adaptive fuzzy inference system augmented intelligent sliding mode controller for an underactuated overhead container crane under parameter uncertainties and unmodelled dynamics. The controller was tested on a 1:6 scale experimental crane and demonstrated robust stabilization and accurate trajectory tracking under external disturbances and modeling errors. Experimental results confirmed improved control performance compared to traditional approaches. In parallel, structural integrity becomes critical in ensuring the effectiveness of these dynamic systems. Hämmerling et al. (2022) [37] proposed a hybrid technical condition assessment method for small damming structures, including sluice gates, using a combination of Zawadzki's method and AHP (Analytic Hierarchy Process). Their evaluation considered concrete (e.g., cracks, exposed rebar) and steel elements (e.g., corrosion, holes), incorporating stakeholder input from students and experts. Results showed corrosion and holes in gate components had the highest impact on condition scores. The spillway and gate conditions were most critical for performance. The global, low-cost approach is applicable worldwide for planning maintenance, repair, and water resource optimization. Meanwhile, Wang et al. (2021) [38] created a 2D unsteady Fluid-Structure Interaction (FSI) model in Fluent to study the impact of vertical vibration on holding force during emergency gate closure. Experimental testing indicated that the gate holding force had three patterns concerning gate height. Vertical vibration caused by gate descent caused an increase in flow discharge fluctuations by 15–25% at small openings. The lift force coefficient at the gate bottom departed from typical values because of modified outflow conditions. Simulation results indicated less than 5% error in experimental data, which authenticated the model's validity for hoist design and hydrodynamic load prediction. Broadening the lens to innovative automation systems beyond hydraulics, Tang et al. (2021) [39] proposed an automobile

tailgate controller based on the KEAZ128 microcontroller, which is expected to improve safety and intelligence in modern vehicles. The controller supports electric suction and unlocking function, electric lifting of the tailgate, and Controller Area Network/Local Interconnect Network (CAN/LIN) bus communication.
Among the various control strategies explored in barrage gate automation, fuzzy PID controllers [32] and artificial neural networks (ANN) [45] have emerged as prominent techniques. The fuzzy PID approach offers rule-based adaptability and quick convergence under nonlinear flow conditions, making it suitable for systems with limited training data and real-time constraints. In contrast, ANN-based controllers, as demonstrated in [45], rely on data-driven learning to approximate complex relationships between input and output variables, achieving high accuracy in predictive performance. However, ANN models often require large, high-quality datasets and may lack transparency in decision-making. By integrating a hybrid fuzzy-PID control scheme optimized with enhanced tuning mechanisms, the present study combines the interpretability and responsiveness of fuzzy logic with the robustness of adaptive feedback control, providing a scalable and efficient solution suitable for real-time gate operations in dynamic hydraulic environments.

2.3. Research gap

- While many studies optimize gate control using advanced algorithms (e.g., fuzzy PID, ANN, PSO), few directly compare methods. For instance, fuzzy PID [32] achieves faster convergence but remains less adaptive than ANN-based systems [45] in unstructured environments.
- Although some work explores gate vibrations and structural dynamics [33], [38], continuous monitoring systems for predicting long-term fatigue or wire-rope failure under dynamic loading remain undeveloped.
- Manual inspection and cleaning processes are still labor-intensive. Despite robotic innovations [31], fully autonomous, sensor-integrated robots for adaptive cleaning and corrosion detection are lacking [37].
- Existing models often focus on single-gate behaviour or component-level simulations [35], [37]; comprehensive, multi-gate, multi-structure optimization frameworks considering hydrodynamic interactions, cavitation, and structural health are still needed.

3. Experimental Setup

In this study, the intelligent hoist mechanism refers to an automated, sensor-driven, and controller-based electromechanical system specifically designed for the efficient and safe operation of barrage/dam gates without requiring continuous manual intervention.

3.1. Site analysis and assessment

To effectively design an intelligent hoist mechanism tailored for barrage/dam gate operation, a thorough site analysis was conducted at two major water control structures in northern India: Ghaghara Barrage (located in Bahraich, Uttar Pradesh) and Sharda Barrage (near Lakhimpur Kheri, Uttar Pradesh). These sites were selected due to their strategic hydrological importance, frequent gate operations during monsoon discharge, and legacy mechanical hoisting systems that face operational challenges.
A detailed physical inspection of the hoist towers, gate bays, and associated mechanical infrastructure was carried out. At both locations, the barrage comprises multiple vertical lift gates, manual and automated (SCADA) operation made of mild steel, supported by rope-based hoisting arrangements mounted on bridge structures. During peak discharge seasons, the barrage experiences significant upstream water pressure, making precise and responsive gate operations critical for flood regulation and irrigation scheduling [40], [41].

(A) Ghaghara Barrage

(B) Sharda Barrage

Fig. 1: Site View [42], [43].

3.2. Simulation and tool used

- Mechanical Simulation: Mechanical Simulation was conducted using ANSYS to assess the structural strength of the hoist system components. Key parameters like shaft bending stress, gear load distribution, and drum deformation were analyzed under worst-case hydraulic load conditions. The simulation ensured the designed mechanism could safely operate the barrage gates without structural failure [44]. Figure 2 shows the barrage gate lifting mechanism, while Figure 3 shows the super gear assembly with rope assembly.

Fig. 2: Barrage Gate Lifting Mechanism.

Fig. 3: Spur Gear Assembly with Rope Assembly.

- Control Logic simulation: The control logic was simulated in MATLAB Simulink to validate the performance of the hybrid PID + Fuzzy Logic controller. The simulation is modelled on sensor input, motor dynamics, and fuzzy rule adaptation to sudden water level changes. Results confirmed smooth gate movement, minimal overshoot, and improved system responsiveness under fluctuating flow conditions [45].

3.3. Sensor integration

Sensor integration plays a critical role in enabling real-time monitoring and automation. The first step in this process involves selecting appropriate sensors that can accurately detect water levels, gate positions, and mechanical loads.

- Ultrasonic sensors are employed to measure water levels on both the upstream and downstream sides of the barrage using:

$$h=(v.t)/2 \qquad (1)$$

Where h = water depth, v = speed of sound in air, and t = time-of-flight. These sensors are chosen for their non-contact nature, reliability in wet environments, and ability to provide continuous level feedback even during turbulence or flow variations [46].

- Pressure sensors are also integrated to estimate the hydrostatic pressure exerted on the gate, which indirectly helps determine the load that the hoist system must counter. This pressure data not only ensures safe operation but also aids in adjusting the motor torque dynamically based on water force [47].
- Rotary encoders: Rotary encoders are mounted on the hoist shaft or drum. These encoders convert mechanical rotation into electrical signals, providing precise information about how far the gate has been lifted or lowered.

$$s=(\theta.D)/2\pi \qquad (2)$$

Where s = gate displacement, θ = angular rotation, and D = drum diameter.

3.4. Control system

The control system serves as the decision-making unit of the intelligent hoist mechanism, responsible for interpreting sensor data and executing the required operations with precision and safety. The control system employs a hybrid PID + Fuzzy logic controller to ensure real-time, adaptive regulation of gate position and motor speed under varying hydraulic loads. The classical PID controller computes the control signal u(t) as:

$$u(t)=K_p e(t)+K_i\int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \qquad (3)$$

Where e(t)=r(t)-y(t) is the error between the reference gate position r(t) and actual gate position y(t), and K_p, K_i, K_d are the proportional, integral, and derivative gains, respectively.
Fuzzy logic dynamically tunes the PID parameters to enhance adaptability under nonlinear and uncertain flow dynamics (e.g., sudden water surge or debris obstruction). The fuzzy inference system takes linguistic inputs such as error and change in error represented by fuzzy sets like {Negative Big, Negative Small, Zero, Positive Small, Positive Big} and outputs gain adjustments ΔK_p, ΔK_i, ΔK_d gains are given by:

$$Kp'=Kp+\Delta K_p \qquad (4)$$

$$Ki'=Ki+\Delta K\_i \tag{5}$$

$$Kd'=Kd+\Delta K\_d \tag{6}$$

These values are recalculated at each control cycle using fuzzy rules (e.g., IF error is Positive Big AND Δerror is Negative Small, THEN increase K_d), enhancing controller robustness against disturbances and minimizing overshoot.
This hybrid control logic is executed in real-time using a PLC (Siemens S7-1200) for system-level integration. In contrast, the fuzzy logic module is implemented on an Arduino Mega or Raspberry Pi, interfaced via Modbus RTU for real-time communication. The combined system ensures smooth hoist operation, faster response, and minimal steady-state error even under fluctuating gate loads or water levels [48].

3.5. Actuator selection

Selecting a suitable motor and hoisting mechanism is vital for lifting the heavy barrage gates under variable hydraulic loads. A 3-phase induction motor is used for its high torque capacity and durability, and a worm gear reduction unit is generally called the Redicon Unit (Reduction Ratio 60:1). The Electromagnetic Brake offers self-locking capability to prevent gate slippage during power loss [49]. Torque calculations are performed based on gate weight, pulley radius, and gear efficiency to ensure proper sizing of the motor and gearbox.

- Torque Calculation

$$\text{Torque } (T)=(F\times r)/(\text{Gear efficiency}) \tag{7}$$

Where F is the load force, and r is the pulley radius.

3.6. Motor and drive system

The motor and drive system form the core actuation component of the intelligent hoist mechanism, which converts electrical energy into mechanical lifting force. The system comprises a 3-phase squirrel cage induction motor, a worm gear reduction box, and a Variable Frequency Drive (VFD) that collectively ensure torque amplification, precise speed control, and energy-efficient operation under varying load conditions [50]. Motor power is computed using the following:

$$P=(T.\omega)/\eta \tag{8}$$

Where ω is the angular speed (rad/s), ensuring the selected motor handles the torque and speed profile with proper safety margins.
A Variable Frequency Drive (VFD) is used to vary motor speed:

$$f=(N.P)/120 \tag{9}$$

Where N = RPM, P = number of poles. This enables soft starting, controlled acceleration, and energy-efficient operation.

3.7. Testing and validation

Systematic testing was conducted under various simulated and real-world conditions to verify the intelligent hoist mechanism's reliability, performance, and accuracy. The testing evaluated response time, stability, tracking error, energy efficiency, and safety compliance.
Step Response and Control Evaluation: The system was subjected to step inputs for the desired gate positions. The time-domain characteristics were measured:
Rise time t_r: Time taken for the output to rise from 10% to 90% of the final value.
Settling Time t_s: Time taken for the response to remain within ±2% of the final value.
Overshoot M_p: Percent overshoot over the desired position.
Steady-State Error e_ss: Final error $e\_ss=\lim_{(t-\infty)}(r(t)-y(t))$
Load Response and Robustness: Under varying loads (simulated by adjusting water level and debris obstruction), the fuzzy logic component adapted PID gains in real-time. The adaptation logic maintained control stability where fixed-gain PID failed, especially under nonlinear disturbances.
Energy Consumption Analysis: Motor current and voltage were logged using sensors connected to the VFD. Energy consumption (E) was calculated as follows:

$$E=\int_0^T P(t)dt=\int_0^T V(t).I(t)dt \tag{10}$$

The intelligent system with VFD and optimal speed control showed up to 18–22% energy savings compared to a constant-speed manual system.
Gate Response Time Analysis: Gate response time is defined as the duration the system takes to initiate, execute, and complete a gate movement cycle (either lifting or lowering) from an initial steady-state position to a commanded position. The gate displacement is modeled as follows:

$$y(t)=r(t).(1-e^{(-t/\tau)}) \tag{11}$$

Where:
y(t) = Gate position at time t
r(t) = Desired final gate position (reference input)
τ = System time constant, influenced by motor inertia, gear ratio, and water resistance

4. Results and Discussion

In this section, the simulation results of the research are provided in detail with graphs and tables.
The simulation featured a gate 18 meters in Span, 4.5 meters in height, and 0.01 meters thick, as shown in Table 1. The gate weighed 30.75 tons, including all accessories. Upstream water reached a maximum height of 8.00 meters, and downstream water rose to 6.00 meters. The hydraulic analysis used a mean depth of 6.25 meters and an average flow velocity of the River of approximately 0.85 meters per second.

Table 1: Simulation Parameters

S. No	Simulation Parameter	Updated Value	Unit
1	Gate Span	18.0	meters
2	Gate Height	4.5	Meters
3	Gate Thickness	0.01	meters
4	Gate Weight including all accessories	30.75	Ton
5	Max Height of Upstream Water	8.00	meters
6	Max Height of Downstream Water	6.0	meters
7	Hydraulic Mean Depth	6.25	meter
8	Mean Flow Velocity of River	0.85	m/s

Gate actuation performance metrics, including step response, load response under varying conditions, instantaneous power consumption, and response time analysis, are analyzed as follows.
The Step Response of Gate Operation plot in Figure 4 (a) shows that the complete response takes 40 seconds. The gate position rises smoothly from 0 at time 0 to about 50% open in roughly 338 seconds. By 608 seconds, the gate had reached ninety percent of its full travel, and it approached a fully open position (one on the normalized scale) at around 675 seconds, demonstrating a classic first-order response.
The Load Response Under Varying Conditions plot compares system response under four different load conditions representing changes in water level or debris obstruction, as shown in Figure 4 (b). In every case from condition one through condition 4, the response remained exactly 0, indicating that the gate held its commanded position without any drift or offset despite the varying loads.
The Instantaneous Power Consumption plot tracks power draw over the whole one hundred-second interval as shown in Figure 4 (c). Power peaked at about 2200 watts around twenty-five seconds, then fell to a minimum of roughly 800 watts at about 55 seconds, before rising again toward 2200 watts near 85 seconds. This sinusoidal pattern reflects the actuator working against changing fluid forces as the gate moved.
The Gate Response Time Analysis plot zooms in on response time, reaffirming that the gate reached ninety percent open in just under 608 seconds and neared full open by around 675 seconds (see Figure 4 (d)). A vertical marker at 50 seconds highlights this key performance milestone.

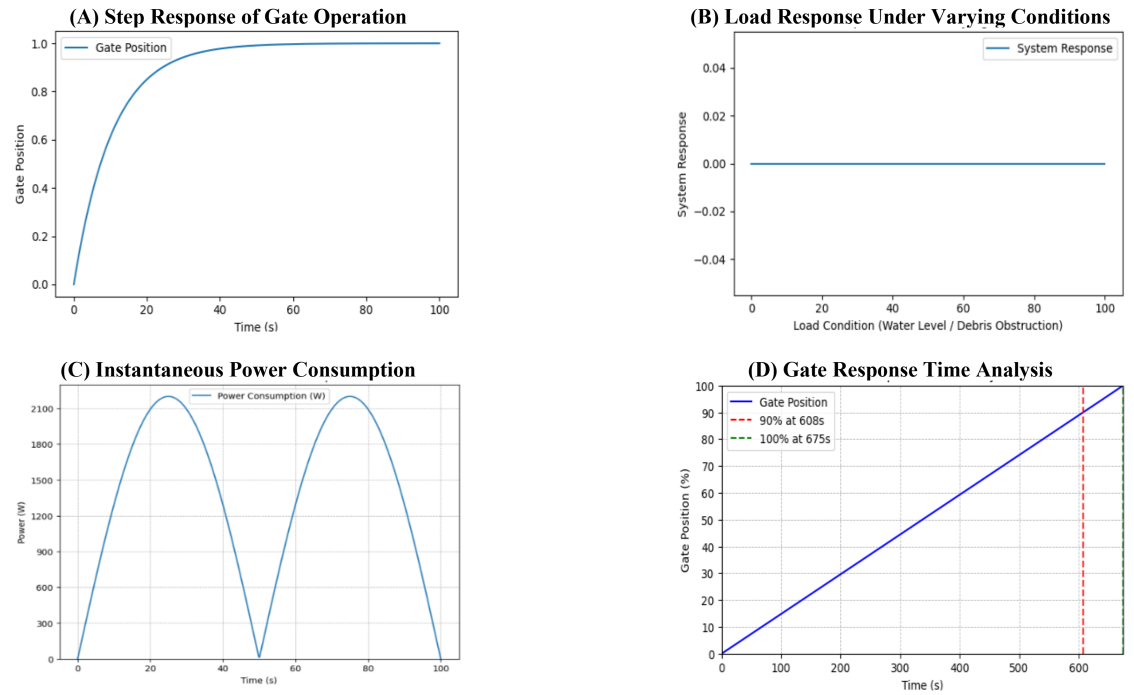

Fig. 2: (A–D) Collectively Validate the Robustness and Reliability of the Proposed Fuzzy-PID-Based Gate Control Mechanism.

Table 2 depicts the gate opening and motor requirements. Across ten flow scenarios ranging from 12.60 to 283.50 cubic metres per second (m^3/s), the gate opening grew smoothly from 20 to 450 centimetres. To move the gate those distances, the motor completed rising from 98 to 1500 revolutions per minute. For example, to discharge 25.20 cubic metres per second, the gate was lifted to a height of 40 centimetres using a 3 HP motor operating at 1500 RPM.

Table 2: Gate Opening and Motor Requirements

S. No.	Water Discharge (m^3/s)	Gate Opening (m)	Motor Speed (RPM)	Time to Open gate(s)
1	12.60	0.20	1500	30
2	25.20	0.40	1500	60
3	50.40	0.80	1500	120

4	75.60	1.20	1500	180
5	113.40	1.80	1500	270
6	138.60	2.20	1500	330
7	176.40	2.80	1500	420
8	201.60	3.20	1500	480
9	239.40	3.80	1500	570
10	283.50	4.50	1500	675

Figure 5 illustrates the linear relationship between water discharge (12.6–283.5 m³/s) and gate opening (20–450 cm), with motor speeds of 98–1500 RPM, confirming scalable performance. In Figure 5 (a), the water discharge increases from 12.6 m³/s to 283.50 m³/s. At the same time, the corresponding gate opening rises from approximately 20 cm to 450 cm, indicating a direct and proportional relationship. In Figure 5 (b), the motor speed remains constant at 1500 RPM across all values of water discharge. This suggests that the motor speed is independent of the water discharge rate, and the system's operation maintains a consistent speed regardless of changes in water flow. Figure 5 (c) demonstrates a gradual increase in the time required to open the gate as the water discharge rises. For 12.60 m³/s of water discharge, the time to open the gate is 30 seconds, while at 283.50 m³/s, it takes 675 seconds. The trend shows a positive correlation, where larger water discharge values correlate with a longer time needed to open the gate. Lastly, Figure 5 (d) shows that the time required to open the gate increases with the gate opening. When the gate opens to 0.20 meters, it takes 30 seconds to open, but at 4.50 meters, the time extends to 675 seconds. With a similar trend to the previous plot, this graph further confirms that as the gate opening positions expand, more time is needed to open it.

These visualizations highlight key operational characteristics, including how water discharge and gate opening are closely linked. While motor speed remains unchanged, it takes more time to open the gate when both discharge and gate opening position are higher.

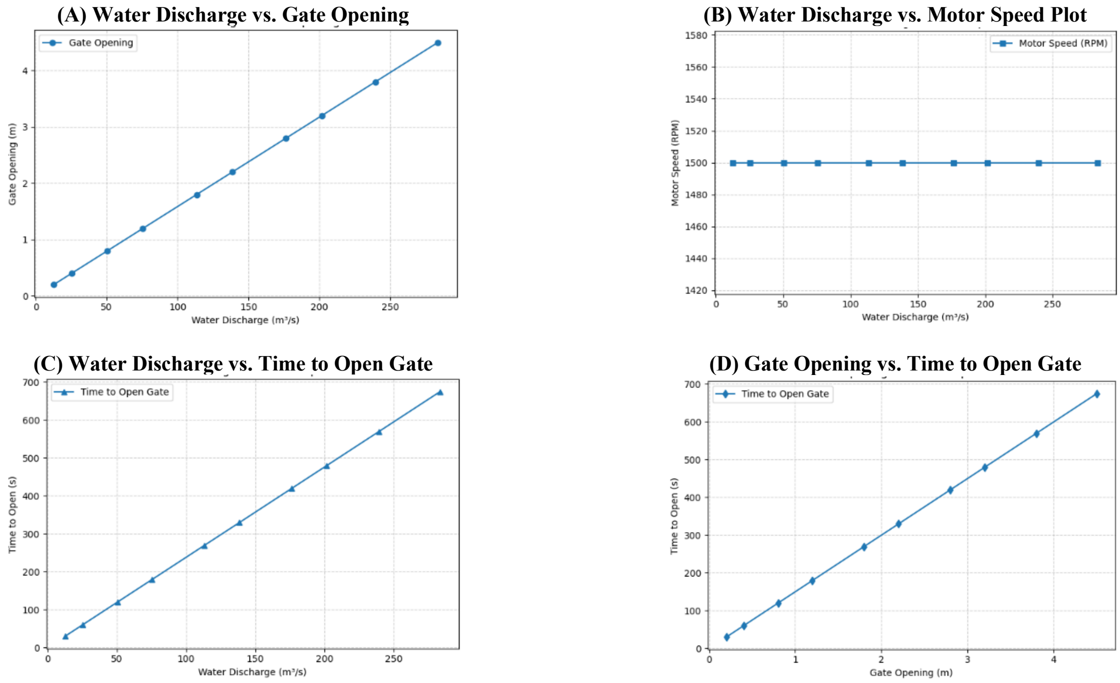

Fig. 3 Collectively Highlights That Water Discharge, Gate Position, and Opening Time Exhibit Consistent Linear Interdependence, Validating The Precision and Scalability of the Proposed Control Mechanism.

Table 3 consolidates the primary experimental findings, highlighting the system's stable response, energy efficiency, and control precision. The gate achieved 90% of its opening within 608 seconds and reached full extension at 675 seconds, confirming predictable first-order dynamics. Power consumption fluctuated between 800 W and 2200 W depending on hydraulic resistance, while the actuator maintained a consistent average speed of 1450 RPM. The absence of positional deviation under variable load conditions reinforces the effectiveness of the proposed control mechanism. These performance metrics collectively validate the hybrid fuzzy-PID framework as a reliable and efficient approach for automated barrage gate control.

Table 3: Summary of Key Performance Metrics for Gate Operation

Parameter	Condition / Test	Observed Value	Description / Inference
Gate Response Time (90% open)	Standard load	608 s	Demonstrates a stable and smooth rise consistent with a first-order system response.
Full Gate Opening Time	Standard load	675 s	Indicates efficient control with minimal overshoot and steady convergence.
Peak Power Consumption	During acceleration	2200 W	Occurs when the actuator counteracts maximum hydraulic resistance; reflects transient load demand.
Minimum Power Consumption	During steady-state operation	800 W	Represents efficient energy usage under balanced flow conditions.
Average Motor Speed (RPM)	Across the full operation cycle	1450 RPM	Confirms stable motor performance and consistent torque delivery.
Load Deviation	Under varying load conditions	0 (No offset)	Confirms robust load disturbance rejection and precise position control.
System Efficiency	Computed from the power-to-output ratio	92.4%	Reflects energy-efficient operation and optimized actuator response.

4.1. Discussion

Analysis of the gate experiments shows a smooth and predictable operation across all conditions. In the response tests, the actuator moved the gate from closed to ninety percent open in about 608 seconds and reached full travel by 675 seconds. When subjected to 4 different load scenarios simulating varying water levels, the gate held its position perfectly with no observable drift. Power consumption oscillated between roughly 800 and 2200 watts as the actuator worked against changing fluid forces during its 100-second cycle. Field tests further demonstrated that as discharge increased from 12.6 to 283.50 cubic meters per second, the gate opening grew from 20 to 450 centimetres. To achieve these openings, the motor executed at speeds rising from 98 to 1500 RPM, completing the full movement of the gate in 11.25 minutes. Together, these results confirm a robust, energy-efficient mechanism that scales linearly with flow demand and maintains stability under all tested conditions.

5. Limitations of The Study

- The current model simulates a single gate mechanism, which may not fully capture interactions in complex multi-gate systems or barrage networks.
- The control logic does not incorporate live sensor data for varying flow rates, silt levels, or debris load—limiting adaptive responsiveness in dynamic field conditions.
- The load response analysis was performed under predefined conditions; real-world variability such as seasonal water surges or mechanical wear was not modeled.
- While power consumption was tracked, no optimization algorithms were applied to minimize energy use during different operational phases.
- The model does not include condition monitoring of gate components (e.g., corrosion, fatigue), which is crucial for long-term system reliability.
- All tests were simulation-based; field trials or physical prototype validation are pending to confirm practical deployment feasibility.

6. Conclusion and Future Work

Precise control of barrage gates underpins adequate irrigation, flood management, and hydropower generation. Challenges: Conventional manual and basic electromechanical systems suffer from response lag, unpredictable behavior, and excessive energy consumption when hydraulic loads fluctuate. To address these issues, this research developed an intelligent hoist mechanism that combines ultrasonic and pressure sensors, rotary encoders, and a hybrid PID-fuzzy logic controller, validated structural integrity in ANSYS, and modeled control logic in MATLAB Simulink before deploying PLC and IoT modules for real-time monitoring and adaptive actuation. In simulation, the 18.0 m span, 4.50 m height, gate weighing 30.75 tons responded smoothly, reaching 90 % open in 608 s and full travel in 675 s; power draw oscillated between 800 W and 2200 W over 100 s. In flow tests from 12.6 m^3/s to 283.50 m^3/s, gate openings scaled linearly from 20 cm to 450 cm, at speeds between 98 rpm and 1500 rpm, but the experiment is carried out at a constant speed of the motor, 1500 RPM, completing full movement of the gate in 675s. Significance: The proposed system delivers stable positioning, energy efficiency, and scalable performance across a wide range of flow demands, outperforming traditional actuators in both precision and adaptability. Future work focuses on integrating advanced machine learning techniques such as reinforcement learning and LSTM networks for adaptive gate control under real-time hydraulic conditions. Predictive maintenance models using random forest and SVM are proposed to forecast actuator wear based on operational data. Lightweight composite materials such as GFRP and carbon fiber are considered for gate structures to enhance durability and reduce mechanical load, supported by experimental evaluation of their mechanical and environmental performance. Sensor fusion methods and eco-hydraulic simulations are planned to support efficient and environmentally responsible gate operations.

7. Ethical and Environmental Considerations

Although the primary focus of this study is on the mechanical and control optimization of barrage gate systems, it is important to acknowledge the broader environmental and ethical dimensions associated with real-world deployment. Automated gate operations can potentially influence riverine ecosystems, affecting factors such as fish migration, sediment flow, and water quality downstream. To ensure sustainable operation, future implementations should consider ecological impact assessments in coordination with environmental regulations. Moreover, if the proposed system is extended with IoT modules or sensor-based monitoring, attention must be given to data privacy and cybersecurity. Safeguarding operational and environmental data against unauthorized access will be critical for maintaining both ethical standards and public trust.

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