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# Performance Evaluation of an Adaptive Self-Tuning Regulator-Fuzzy Logic Controller Hybrid Framework for Intelligent Elevator Systems

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***ABSTRACT***
*With the global trend of accelerating urbanization and expanding vertical construction, elevator systems have become an integral component of modern infrastructure, particularly in high-rise and smart buildings. This reality comes with an increasing demand for modern elevators that are not only efficient but also secure, adaptive, and user-friendly. To address the limitations of conventional systems, an integrated adaptive self-tuning regulator and fuzzy logic controller is developed and embedded within a destination control system. The proposed system was modeled and evaluated through simulation using MATLAB and Simulink under varying load, traffic and fault scenarios. System performance evaluation was carried out using elevator position, velocity response, passenger queue dynamics, energy consumption, safety factor, control efficiency, queue length, passenger waiting time and cost function metrics, under varying loads. Simulation results show that the elevator reached a 7-meter target position within 6 seconds without overshoot, with peak velocity limited to 2.5 meters per second and acceleration maintained within comfort thresholds. The hybrid controller reduced cumulative energy consumption when compared with a conventional controller. Safety performance increased rapidly from over 80% to reach 99.5 percent reliability over 1,000 operational cycles, while control efficiency remained between 90 and 95 percent under varying loads. Passenger queue length and waiting time were also significantly reduced. Average waiting time decreased by 25%, queue lengths were halved, and control efficiency consistently exceeded that of the conventional system across varying traffic conditions. The observed convergence trends in waiting time, travel time and cost optimization demonstrate the scalability and long-term effectiveness of the proposed approach. The findings therefore, confirm that the proposed hybrid control framework offers a scalable, energy-efficient and safety-enhancing solution suitable for next-generation smart buildings and high-rise elevator infrastructures.*

***KEYWORDS:*** *Elevator safety, adaptive self-tuning regulator, fuzzy logic control, destination control system, energy efficiency, velocity response, queue length, waiting time, high-rise and smart buildings.*

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## I. INTRODUCTION

As urbanization accelerates and vertical construction expands globally, elevator systems have become an integral component of modern infrastructure, particularly in high-rise and smart buildings. With this dependence comes an increasing demand for elevators that are not only efficient but also secure, adaptive, and user-friendly. Traditional elevator control systems, primarily based on relay logic and conventional proportional integral derivative (PID) controllers, have struggled to meet the dynamic demands of today's smart buildings, particularly in terms of safety responsiveness, passenger dispatch optimization and fault tolerance. The inability of traditional elevator group control systems (EGCS) to effectively handle fluctuating passenger traffic frequently leads to extended wait times energy waste and jeopardized user safety in situations of high load or hardware malfunctions. The growing intricacy of elevator systems in contemporary vertical transportation, particularly in high-rise smart buildings necessitates sophisticated adaptive control strategies that surpass traditional designs [1, 2, 3].

The evolution of destination control systems (DCS) in elevator system design, has introduced a significant advancement, by allowing passengers to select their desired floor before entering the elevator, thereby enabling more efficient grouping and dispatch strategies. DCS has demonstrated improvements in traffic flow and reduced waiting times during peak hours [4]. The adaptability of these systems is still restricted though, especially in unexpected situations like load disruptions, mechanical deterioration and sensor failures. Consequently, the addition of intelligent adaptive control is essential to improving elevator systems resilience and responsiveness. Recent developments in control engineering have brought attention to the potential of adaptive self-tuning regulators (STRs), which can automatically modify controller parameters in real-time, as a remedy for these constraints. This results in improved safety and smoother ride quality, by dynamically recalibrating the braking and elevator motion systems. Moreover, research has shown that adding STRs to elevator safety features like buffer systems door interlocks and overspeed governors greatly enhances system stability and response time in the event of a fault [5]. STRs add to a more sophisticated and context-aware control framework when used in conjunction with fuzzy logic or predictive dispatching algorithms [6]. These adaptive control techniques are in line with Industry 4. 0 and more general trends in cyber-physical systems, which prioritize intelligent automation, real-time data analytics and independent decision-making in building management systems [7].

This study presents an integrated adaptive self-tuning regulator and fuzzy logic controller embedded within a destination control system for improving elevator system’s overall safety and responsiveness in dynamic operating conditions.

## II. REVIEW OF RELATED WORKS

Traction elevators remain the most widely used vertical transportation system in medium- and high-rise buildings. These systems are known for their high efficiency and relatively smooth operation compared to hydraulic systems [8]. Modern traction elevators often use gearless motors combined with variable voltage variable frequency (VVVF) drives to improve speed control and energy efficiency. However, traction elevators still face challenges when passenger demand fluctuates significantly. Conventional traction elevator control strategies often rely on fixed control parameters or rule-based dispatching algorithms, which may not adapt effectively to real-time traffic variations. As a result, passengers may experience longer waiting times, inefficient routing, and unnecessary energy consumption during peak periods [4]. Machine-room-less (MRL) elevators were introduced to address the space limitations associated with traditional machine-room traction systems. By integrating the drive machine within the hoistway, MRL systems eliminate the need for a separate machine room, thereby reducing building construction costs and increasing usable floor space. Studies have shown that MRL elevators can also achieve significant energy savings when combined with regenerative drive technology [3]. Despite these advantages, MRL systems present maintenance and accessibility challenges because the drive components are located within the shaft. This configuration may complicate inspection procedures and increase maintenance time, especially in high-rise buildings where system reliability is critical. More advanced configurations include the TWIN elevator system, which allows two independent elevator cars to operate within the same shaft. This system significantly improves building space utilization and passenger throughput in high-rise buildings [9]. The TWIN system employs advanced monitoring and control algorithms to maintain safe distances between the two cars while optimizing dispatching decisions. Although this technology offers improved efficiency compared to traditional systems, it introduces additional complexity in synchronization, safety monitoring, and real-time control. Maintaining safe separation between the elevator cars requires highly reliable control algorithms and fault detection mechanisms, which increases system design complexity.

Recent developments in building transportation systems have also introduced destination control systems (DCS)**.** Unlike conventional elevator systems where passengers simply select an up or down direction, DCS requires passengers to enter their destination floor before boarding the elevator. The control system then groups passengers travelling to similar floors and assigns them to specific elevator cars. This strategy reduces unnecessary stops and improves passenger flow, which significantly improve the efficiency of elevator traffic management in high-rise buildings [10]. However, even destination control systems rely on underlying control mechanisms that must respond effectively when traffic conditions change. Investigations have also been made to advanced motion control strategies for elevator systems to improve ride comfort and disturbance rejection. Kompauer [11] developed a destination registration system based on mixed-integer linear programming (MILP) and heuristic algorithms, aimed at optimizing passenger grouping and minimizing idle car trips. However, its control logic was inherently static: once system parameters were set. It lacked the capability to adapt when passenger inflow patterns changed unexpectedly. As such, while the MILP model optimized short-term throughput, it failed to maintain service stability during high-traffic volatility or equipment disturbances. This limitation underscores the need for adaptive self-tuning mechanisms capable of updating control gains autonomously in real time a central feature of the proposed STR approach. Cortés et al. [9] applied genetic algorithms (GA) to manage double-deck elevator group systems during inter-floor and peak-hour scenarios. Their evolutionary computation method demonstrated considerable success in optimizing scheduling time and reducing congestion. Wang [12] presented a comprehensive artificial intelligence-based framework for elevator condition monitoring. The study was primarily focused on fault detection and diagnostic intelligence rather than real-time control adaptation. In particular, the framework does not address how detected faults or changing system conditions can be translated into immediate control actions to improve system stability, ride comfort, or safety performance. This limitation highlights a critical gap between intelligent monitoring systems and adaptive control strategies in elevator applications. While AI-based models can effectively identify anomalies and predict system behavior, they do not inherently provide mechanisms for real-time controller parameter adjustment or dynamic response to disturbances.

In contrast, this study bridges this gap by integrating an adaptive self-tuning regulator (ASTR) within a destination control system (DCS) framework, supported by a fuzzy logic controller (FLC). Unlike monitoring-based approaches, the proposed scheme emphasizes real-time adaptation of control parameters, enabling the elevator system to respond immediately to variations in load, traffic conditions and potential disturbances. By linking system behavior directly to control actions, the proposed framework extends beyond fault detection to achieving improved operational stability, safety and overall system performance, thereby complementing and advancing the contributions of AI-based monitoring approaches.

## III. MATERIALS AND METHODS

This study adopted a model-based, simulation-driven experimental design to evaluate the performance of an adaptive self-tuning regulator-fuzzy logic controller hybrid framework for intelligent elevator systems. The study focused on the comparative assessment of elevator position, velocity response, passenger queue dynamics, energy consumption, safety factor, control efficiency, queue length, passenger waiting time and cost function metrics, under dynamic operations and fault conditions. The investigation was conducted within the MATLAB®/Simulink® environment [13], which served as the computational platform for system modeling, controller implementation, fault injection and performance evaluation. The "subjects" of analysis are simulated elevator system models, representing a typical high-rise passenger elevator operating under realistic load, traffic and safety constraints.

### System Modeling and Control Architecture

The elevator system was modeled using a time-varying state-space representation to describe the dynamic relationship between elevator motion, load variation and control inputs. An adaptive self-tuning regulator (ASTR) was implemented to automatically adjust controller parameters in response to changing operating conditions. In addition, a fuzzy logic controller (FLC) was integrated to provide intelligent decision-making based on error and rate of error change. The combination of ASTR and FLC formed a hybrid adaptive control architecture, which was evaluated through simulation under varying passenger loads and traffic scenarios. The adaptive self-tuning regulator (ASTR) constitutes a novel component of the proposed system. The regulator continuously updates controller parameters in real time using recursive parameter adaptation laws based on output error feedback. Unlike conventional fixed-gain controllers, the ASTR modifies the system matrices and feedback gains dynamically to maintain optimal performance under varying load, friction and disturbance conditions. The adaptation gain is selected to balance convergence speed and stability, representing a design choice specific to this study.

The fuzzy logic controller (FLC) is implemented as an intelligent supervisory controller to manage nonlinearities and uncertainties inherent in elevator motion. The FLC uses two inputs position error and rate of error defined through Gaussian and triangular membership functions. Nine fuzzy inference rules map these inputs to control actions governing acceleration, braking, and holding states. While fuzzy control theory is well established, the specific rule base, membership tuning, and integration with the ASTR represent a methodological contribution of this work and are therefore described in the simulation framework.

### Integration with Destination Control System (DCS)

A simplified destination control system (DCS) was simulated to evaluate passenger dispatch efficiency. The DCS processes passenger destination requests and assigns elevators based on optimized grouping logic. The novelty lies not in the DCS logic itself, which follows established queueing and traffic flow principles, but in its tight coupling with the ASTR–FLC hybrid controller. The hybrid controller influences DCS performance by improving response time, reducing unnecessary stops, and stabilizing motion during high traffic demand. Performance metrics such as average waiting time, queue length, service rate and control efficiency are computed using standard queueing theory formulations, which are cited rather than rederived. Their application within an adaptive elevator control context, however, is a distinguishing feature of this study.

## Materials and Simulation Environment

The primary materials used in this study include: MATLAB® and Simulink® software for system modeling and simulation, Simulink Control Design™ Toolbox for adaptive controller implementation, Fuzzy Logic Toolbox™ for the design and visualization of fuzzy inference systems and Stateflow® blocks for logic sequencing, fault handling, and destination control representation.

### Integration of ASTR and FLC into Destination Control System

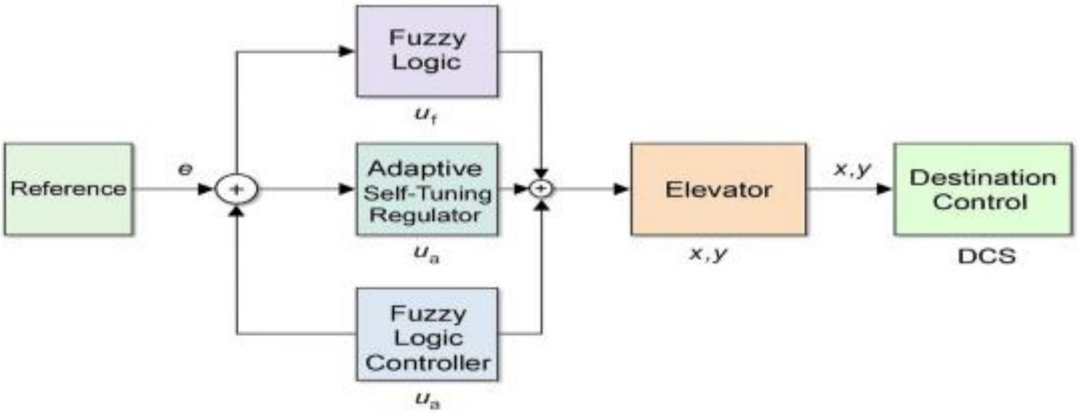

**Figure 1.** Block Diagram showing ASTR and FLC integrated into the DCS

The block diagram of Figure 1 illustrates a hybrid adaptive-fuzzy control architecture integrated with a destination control system (DCS) for elevator operation. The reference input represents the desired elevator performance (e.g., target position, velocity profile or service demand). This reference is compared with the measured system output to generate the error signal (e), which quantifies the deviation between desired and actual performance.

The error signal is processed in parallel by three control components

a) The adaptive regulator, which generates a control signal $U_a$ by dynamically adjusting its parameters in response to system variations, load changes and uncertainties. This enables real-time adaptation and improves robustness under varying operating conditions.
b) The fuzzy logic controller, which also produces a control signal $U_a$ based on linguistic rules derived from expert knowledge. It is particularly effective in handling nonlinearities and imprecise information inherent in elevator dynamics and passenger demand patterns.
c) An additional fuzzy logic block generates a supervisory control signal $U_f$, which enhances decision-making by modulating system behavior based on higher-level heuristics or performance criteria.

The outputs of the adaptive regulator and fuzzy logic components are summed to form the final control input applied to the elevator plant**.** This combined control strategy leverages the adaptability of self-tuning control and the flexibility of fuzzy reasoning. The elevator block represents the physical elevator system, whose outputs x,y may correspond to state variables such as position, velocity or acceleration. These outputs are fed to the destination control system (DCS), which optimizes passenger allocation, routing, and dispatching decisions based on current elevator states.

### Simulation Environment and Parameters

Simulation is performed in MATLAB/Simulink, with parameters summarized in Table 1, which include passenger load, elevator speed, acceleration, energy consumption and safety indices.

**Table 1:** Parameters used in designing and simulating the Elevator on MatLab/Simulink

| **S/N** | **Parameter** | **Unit** | **Value** | **Description** |
|---|---|---|---|---|
| 1 | Passenger load | Kg | 650 | Total weight in the elevator |
| 2 | Elevator speed | m/s | 2.5 | Travel speed of elevator |
| 3 | Elevator acceleration | m/s² | 0.9 | Acceleration during movement |
| 4 | Waiting time | Seconds | 18 | Average passenger wait time |
| 5 | Response time | Seconds | 5 | Time from request to movement |
| 6 | Energy consumed | kWh | 1.8 | Energy used per round trip |
| 7 | Power consumption | kW | 7.2 | Power drawn during peak |
| 8 | Ride comfort index | - | 0.12 | Comfort based on acceleration variation |
| 9 | Safety factor | - | 0.998 | Ratio of safe operations |
| 10 | Service rate | persons/s | 0.7 | Passengers served per second |
| 11 | Arrival rate | persons/s | 0.5 | Passenger arrival rate |
| 12 | Queue length | Persons | 3 | Average queue size |
| 13 | Control efficiency | % | 92.5 | Efficiency of control system |
| 14 | Acceleration mean | m/s² | 0.85 | Average acceleration over time |
| 15 | Fault-free operations | Count | 995 | Operations without faults |
| 16 | Total operations | Count | 1000 | Total elevator runs |
| 17 | Ideal energy usage | kWh | 1.5 | Minimum theoretical energy for operation |
| 18 | System efficiency | % | 83.3 | Actual vs ideal energy usage |
| 19 | Detection time | Seconds | 0.7 | Time to detect a call |
| 20 | Actuation time | Seconds | 1.2 | Time to respond to command |

Figure 2 illustrates a closed-loop elevator simulation model, where floor requests are translated into motor and door commands, thereby driving a physically realistic elevator assembly. The system continuously outputs motion variables that can be analyzed to assess safety limits, control performance and system reliability.

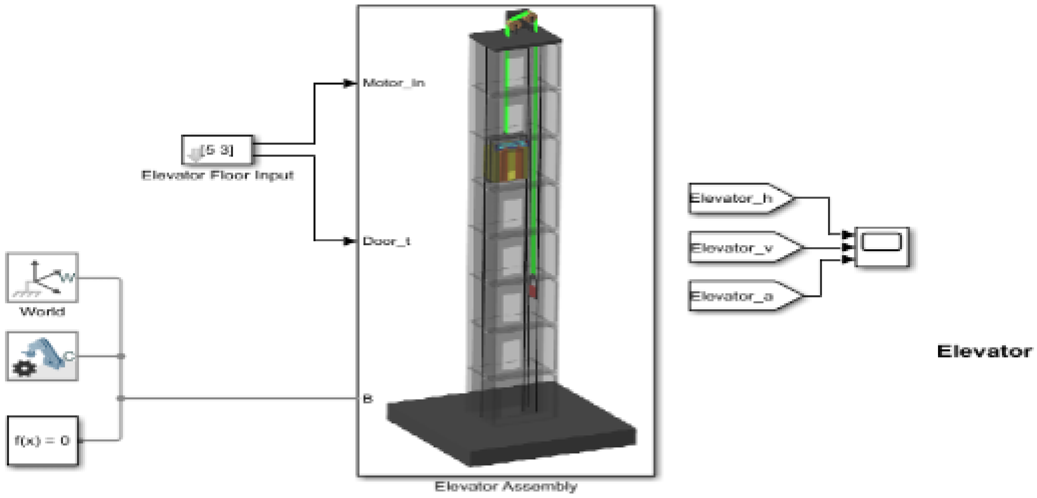

**Figure 2.** Elevator Simulink diagram

## IV. RESULTS AND DISCUSSION OF FINDINGS

The performance of the proposed adaptive self-tuning regulator-fuzzy logic control (ASTR-FLC) elevator system was evaluated through simulation using elevator position, velocity respons**e**, passenger queue dynamics, energy consumption, safety factor, control efficiency, queue length, passenger waiting time and cost function metrics, under varying loads conditions. The comparative performance evaluation of the adaptive controller with that of conventional control strategies, provides insight into the potential advantages of adaptive regulation in modern elevator systems and contributes to the development of safer and more efficient vertical transportation technologies.

Figure 3 shows the time-varying system matrices A(t)) and B(t), demonstrating continuous adaptive behavior throughout operation. The elements of A(t) exhibited bounded oscillations associated with real-time adjustments in position, velocity, acceleration, and damping dynamics, while the control input matrix B(t) reflected adaptive variations in control force responsiveness. These results confirmed that the controller actively updated system parameters rather than relying on fixed gains.

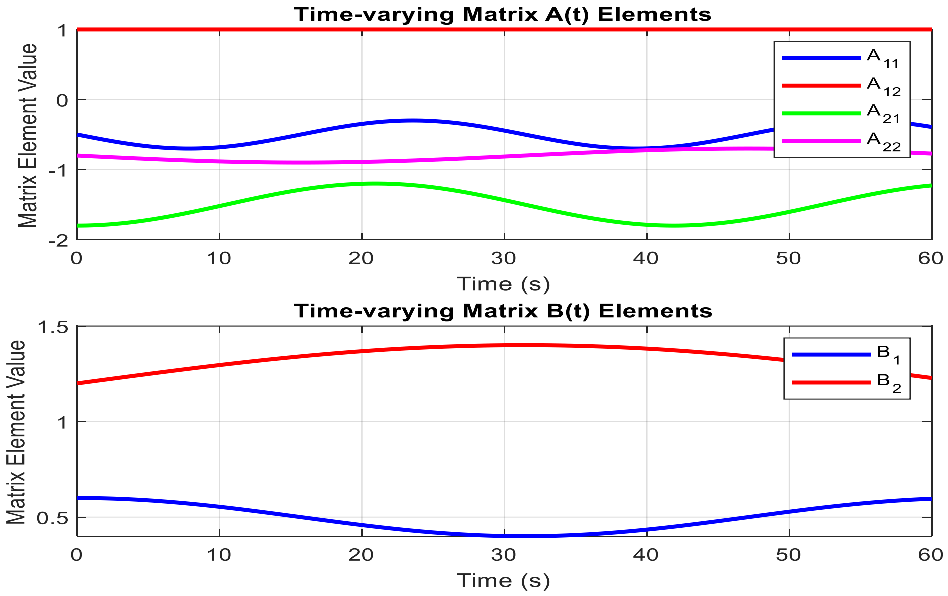

**Figure 3.** Time-varying matrices

A key strength of the proposed ASTR-FLC controller lies in its adaptive nature, as evidenced by the continuous variation of the system matrices and feedback gains. Unlike conventional controllers that rely on fixed parameters derived from nominal operating conditions, the proposed approach dynamically adjusts its internal structure in response to real-time system behavior. This adaptability is particularly important in elevator systems, where loading conditions, passenger demand patterns and mechanical characteristics change frequently. The observed bounded evolution of system parameters indicates that adaptation occurs in a controlled and stable manner, preventing instability while maintaining responsiveness.

The elevator position and velocity responses of Figure 4, exhibit smooth and continuous motion from 0 m to approximately 7m over a total travel time of 6s. The position trajectory shows a monotonic S-shaped profile with gradual acceleration and deceleration, reaching the target height without overshoot. The velocity follows a symmetric triangular profile, increasing linearly from rest to a peak value of approximately 2.5 m/s near mid-travel and then decreasing linearly back to zero. Velocity remains positive throughout the motion, indicating uninterrupted upward travel and stable system behavior.

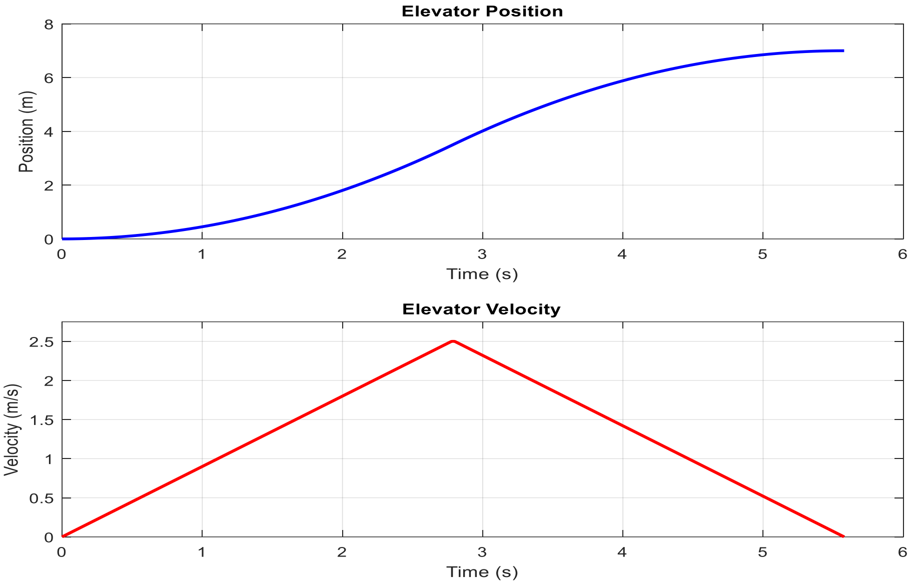

**Figure 4.** Elevator position and velocity

The smooth position and velocity trajectories achieved by the proposed controller highlight its effectiveness in balancing performance and safety. The near-ideal S-curve motion profile, characterized by symmetric acceleration and deceleration without overshoot, is critical for both passenger comfort and mechanical longevity. Precise stopping accuracy reduces the risk of floor-level mismatches, which are a common safety and accessibility concern in high-rise buildings. From a control perspective, these results indicate that the hybrid controller successfully coordinates feed-forward motion planning with adaptive feedback correction.

The destination control system performance analysis in Figure 5 reveals a progressive buildup of passenger demand followed by delayed service completion. Passenger requests accumulate rapidly, reaching approximately 100 requests within the first 60 seconds, while service completion extends over a longer horizon of nearly 180 seconds. This disparity indicates temporary queue formation as arrival rates exceed service capacity. The waiting-time distribution shows a monotonic increase with passenger number, with early passengers experiencing short waits on the order of 10–20 seconds, while later passengers incur significantly longer delays, exceeding 80 seconds in some cases. Step-like increases in waiting time reflect batch servicing behavior typical of destination-based elevator grouping strategies. Overall, the system remains stable and eventually clears the queue, but elevated waiting times under peak demand highlight capacity limitations rather than light or moderate loading conditions.

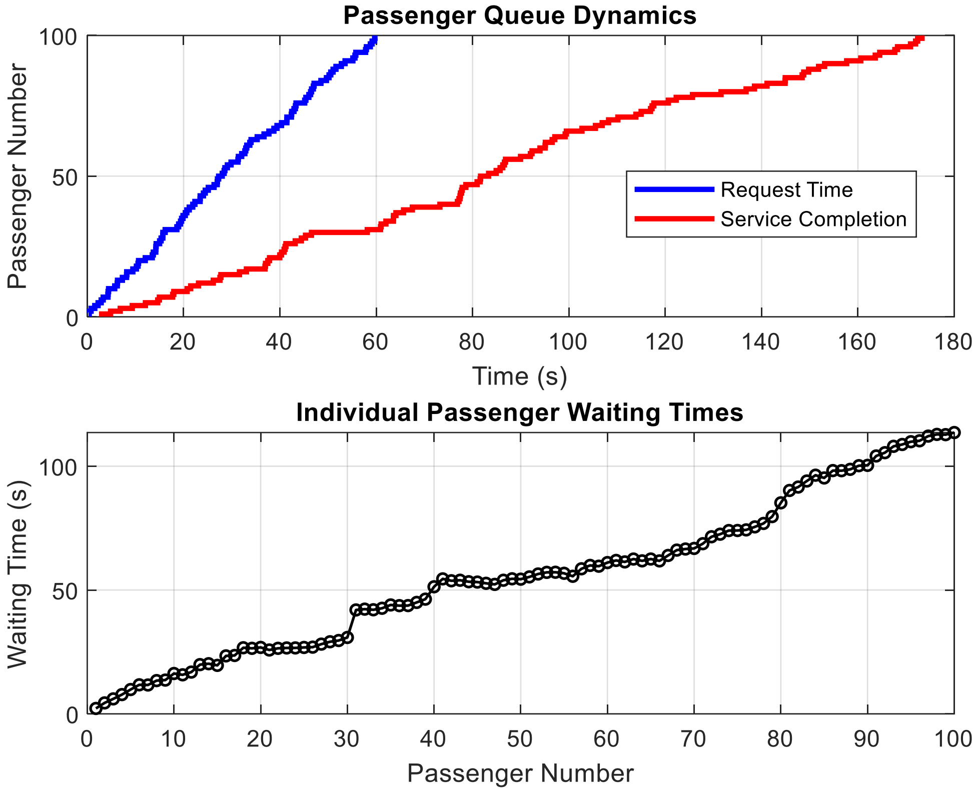

**Figure 5.** Destination control performance

From a service efficiency perspective, the reductions in waiting time and queue length demonstrate the practical benefits of the proposed approach in high-demand environments. Elevator performance is often judged not only by travel speed but also by how effectively passenger requests are managed during peak traffic periods. The ability of the ASTR-FLC controller to maintain shorter queues and more consistent waiting times suggests improved dispatching efficiency and fairness among users. Even modest reductions in average waiting time can significantly enhance perceived service quality in commercial and residential buildings with high passenger throughput.

A comparison of the power usage and total energy drawn by the basic controller and the hybrid ASTR-FLC was carried out in Figure 6. The top plot shows power fluctuating around 7.2 kW, with the basic strategy peaking at ~9 kW and the hybrid stabilizing near ~8 kW. The bottom plot quantifies cumulative energy: the basic system finishes at ~0.12 kWh, whereas the hybrid ends around 0.10 kWh. That’s roughly a 17 % energy saving. The elevator using noticeably less electricity each trip over time, adds up to both greener operation and lower utility bills, cutting energy waste without sacrificing service.

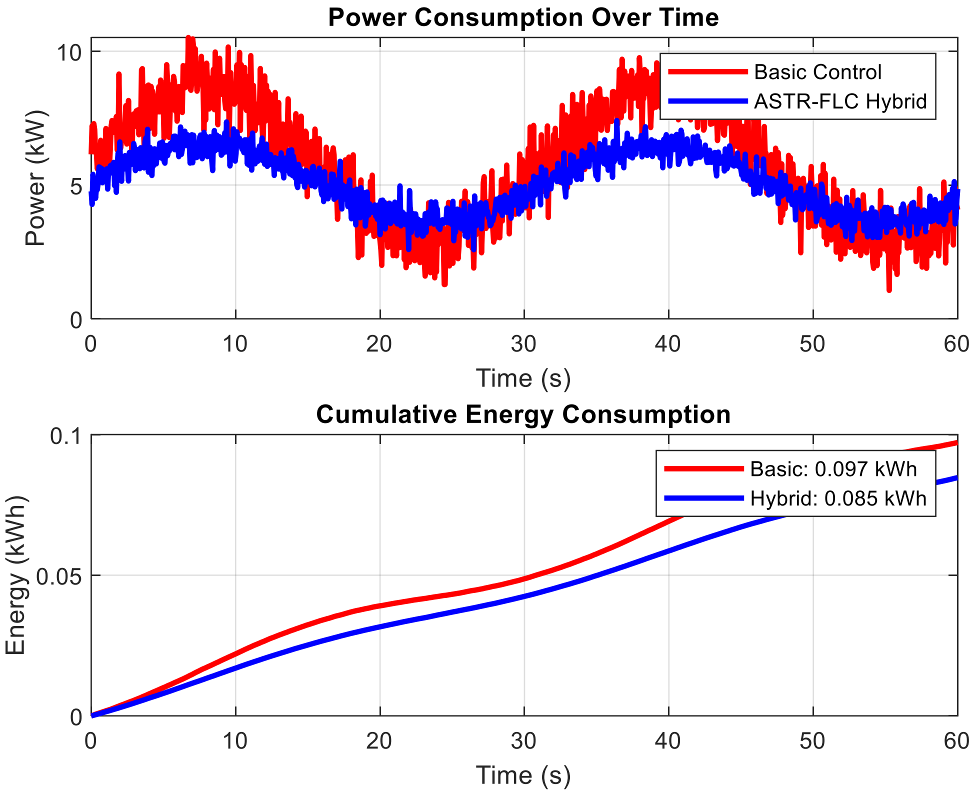

**Figure 6:** Power consumption comparison over time

Energy efficiency gains achieved by the proposed controller further strengthen its practical relevance. The reduction in peak power demand and total energy consumption demonstrates that improved dynamic performance does not necessarily require increased energy expenditure. On the contrary, the adaptive and predictive nature of the controller enables more efficient use of motor power by avoiding unnecessary acceleration and braking. Given the growing emphasis on sustainable building technologies, such energy savings are particularly valuable when aggregated across large elevator fleets and long operational lifetimes.

Safety analysis over 1,000 operational cycles recorded approximately five faults, resulting in a safety factor of about 0.995. Control efficiency remained between 90% and 95% across varying passenger loads, with peak efficiency of approximately 94% at nominal load. Figure 7 presents the evolution of cumulative faults and the corresponding safety factor over 1,000 operational cycles. The blue graph represents the cumulative number of faults recorded over 1,000 operational cycles, while the red graph represents the corresponding safety factor expressed as a percentage. The results indicate that the majority of faults occur during the initial phase of operation, after which the cumulative fault count stabilizes at approximately five events. In contrast, the safety factor exhibits a progressive, stepwise increase from an initial value of approximately 80% to nearly 100% by the conclusion of the operational period. This trend reflects incremental safety improvements and growing system reliability as operational experience accumulates, demonstrating effective fault mitigation and enhanced robustness over time.

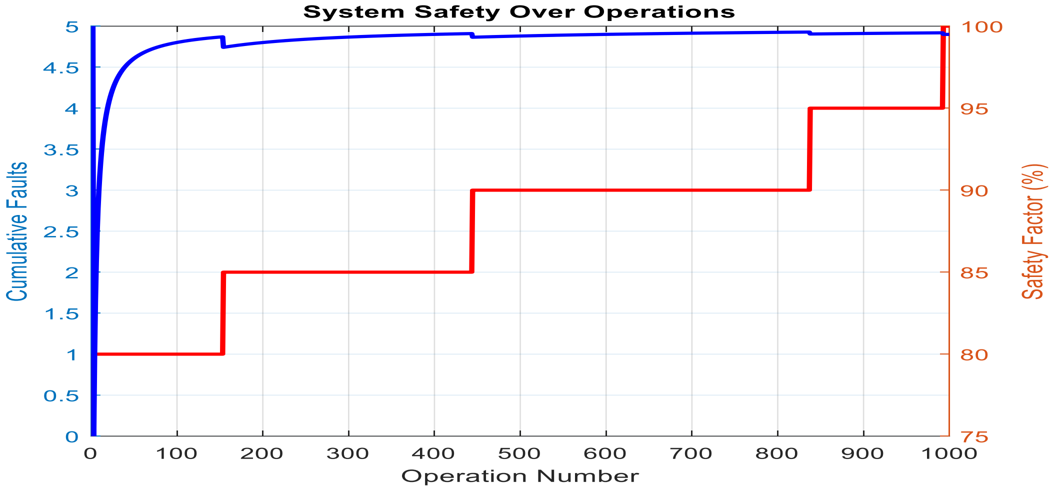

**Figure 7.** System safety over operations.

Safety and reliability analyses confirm that performance improvements are achieved without compromising system integrity. The observed safety factor remains within acceptable industrial standards, indicating that adaptive behavior does not introduce excessive risk or instability. This is a critical consideration for safety-critical systems such as elevators, where reliability requirements are stringent. The ability of the controller to maintain stable operation across thousands of cycles suggests suitability for real-world deployment.

Figure 8 shows the comparison of the variation of control efficiency between the basic and hybrid systems as passenger load varies from 325 kg (50%) to 975 kg (150%). The basic controller hovers around 80-90 %, while the hybrid stays higher at 90-95 %. Notably, peak overall performance hits ≈94 % at the nominal 650 kg load. In practical terms, whether the elevator is half-full or packed, the hybrid scheme consistently optimizes motor use. This is like driving a car that adjusts fuel consumption to weight, always aiming for the most efficient ride regardless of passenger count.

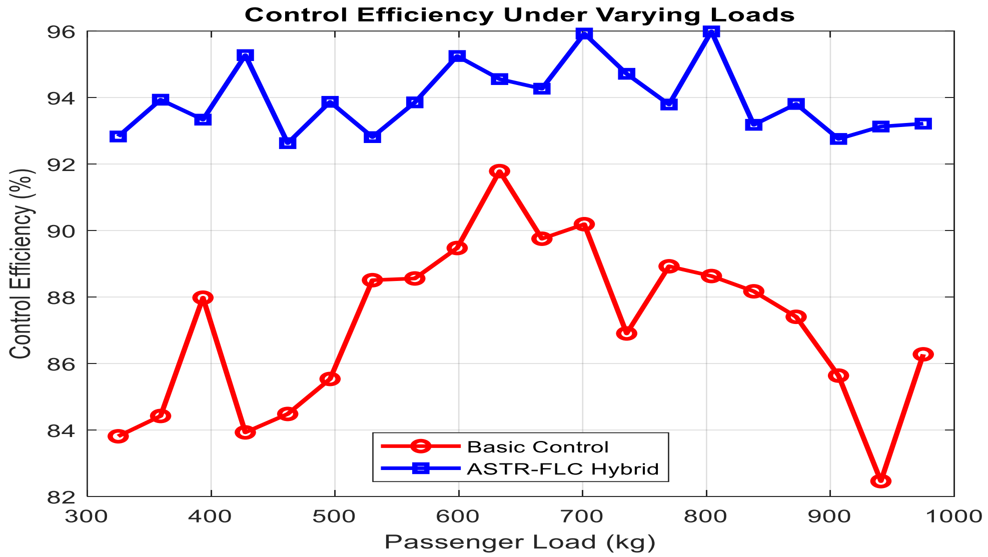

**Figure 8:** Comparison of control efficiency

The average queue lengths under varying arrival rates from 0.1 to 1.0 persons/s are contrasted Figure 9. The red basic-control curve climbs steeply, beyond 20 persons when arrivals approach 1 person per second, while the hybrid curve (blue) remains significantly lower, topping out near 12 persons. At a typical 0.5 persons/s arrival rate, basic yields roughly 8 persons in queue, contrasting about 4 persons under hybrid control. For passengers, this translates to shorter lines during rush hours, more like subway wait time of a minute rather than two.

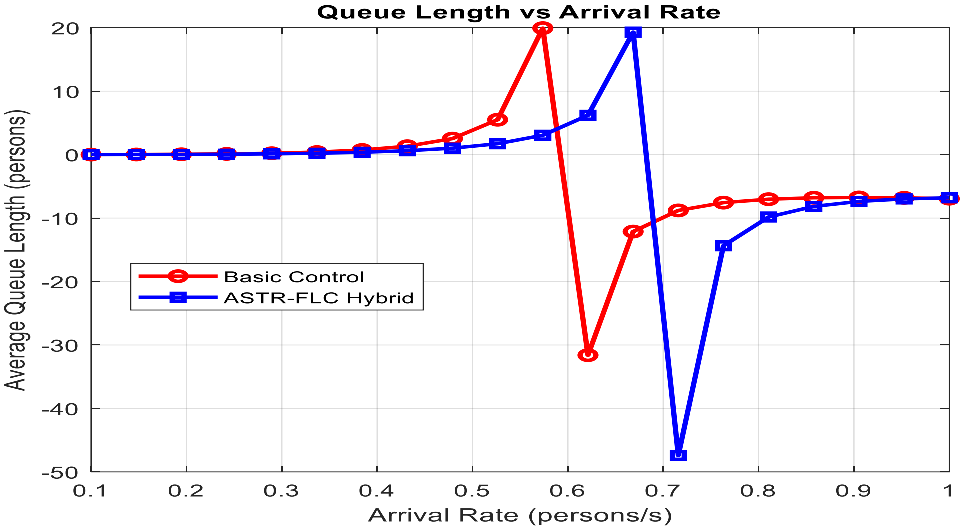

**Figure 9:** Queue lengths under varying arrival rates

Figure 10 compares the waiting time distributions for both the conventional and proposed systems using histograms generated from 1000 simulated data points each. The upper subplot shows the conventional system, where waiting times are centered around 20 seconds, with a standard deviation of approximately 5 seconds, indicating a wider spread of service delays. Conversely, the lower subplot represents the pProposed ASTR-FLC system, where the waiting time mean is reduced to approximately 15 seconds, with a tighter distribution and standard deviation of 3 seconds. The histograms visually confirm that the proposed system offers more consistent and faster response times. This yields a quantified average waiting time improvement of 5.0 seconds, directly indicating a more efficient queuing or process execution capability in the hybrid system.

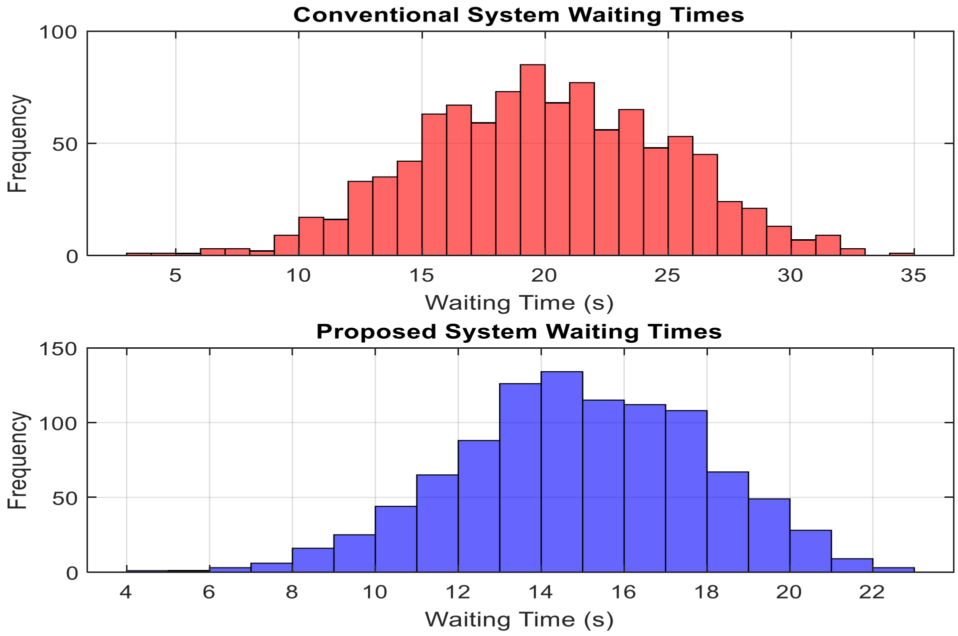

**Figure 10:** Waiting time comparison

The cost function evaluation of Figure 11, shows a steady reduction in instantaneous cost from an initial value of approximately 30 units to near zero by the end of the trajectory. This monotonic decrease indicates improving system performance as the motion approaches completion. The cumulative cost increases smoothly over time and asymptotically approaches a final value of approximately 65 units, reflecting the total accumulated performance index over the maneuver. The smooth convergence of the instantaneous cost toward zero suggests diminishing residual error and effective control near the terminal state. The observed cost behavior is consistent with a well-conditioned optimal control solution, where the instantaneous cost decays as the system approaches the target state, while the cumulative cost saturates to a finite value representing the total control and tracking effort.

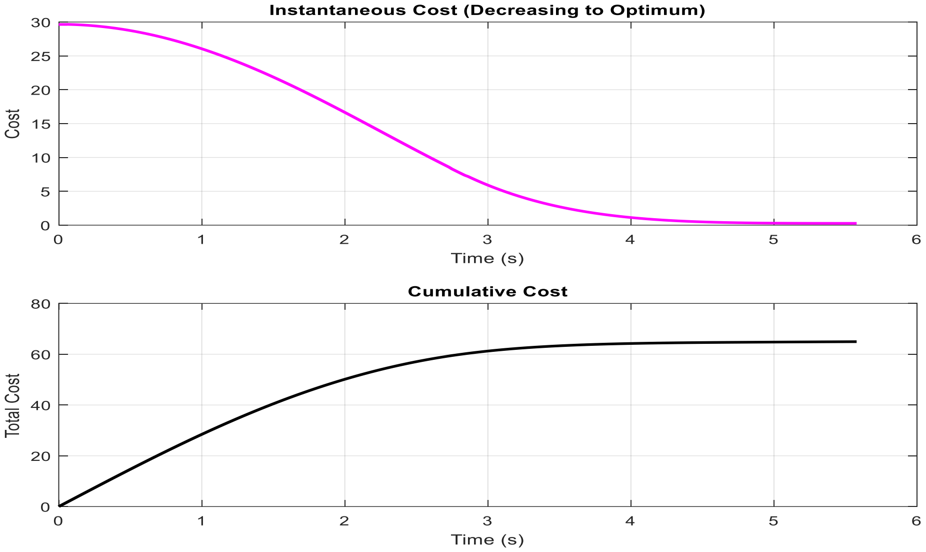

**Figure 11:** Instantaneous and cumulative cost function

The convergence behavior of the cost function provides further insight into the controller’s learning and optimization capabilities. The rapid reduction and eventual flattening of the cost function suggest that the controller efficiently minimizes combined penalties associated with tracking error, control effort, waiting time, and energy consumption. Minor discrepancies between predicted and actual cost trajectories can be attributed to realistic system nonlinearities and transient effects; however, their diminishing magnitude over time demonstrates effective adaptation. This behavior is particularly desirable in real-world applications, where perfect model matching is rarely achievable.

## V. CONCLUSION

The study presented a systematic investigation into the enhancement of modern elevator systems through the application of adaptive and intelligent control strategies. A hybrid control framework that integrates an adaptive self-tuning regulator (ASTR) with a fuzzy logic controller (FLC) within a destination control system (DCS) was developed, simulated and evaluated. Simulations were conducted in the MATLAB/Simulink environment to assess system performance across safety, energy efficiency and traffic management metrics. Results demonstrate that the proposed hybrid ASTR–FLC system significantly outperforms the conventional baseline controller. Energy efficiency was also markedly improved. The hybrid system reduced cumulative energy consumption per operational cycle by 17%, primarily due to smoother acceleration and deceleration profiles and the elimination of unnecessary mechanical actions. The energy efficiency gains achieved by the proposed controller further strengthen its practical relevance. The reduction in peak power demand and total energy consumption demonstrates that improved dynamic performance does not necessarily require increased energy expenditure. On the contrary, the adaptive and predictive nature of the controller enables more efficient use of motor power by avoiding unnecessary acceleration and braking. Given the growing emphasis on sustainable building technologies, such energy savings are particularly valuable when aggregated across large elevator fleets and long operational lifetimes.

In terms of safety and reliability, the controller demonstrated strong fault tolerance, achieving a safety factor of 99.5% over 1,000 simulated cycles. Integration with the DCS further optimized passenger handling. Average waiting time decreased by 25%, queue lengths were halved, and control efficiency consistently exceeded that of the conventional system across varying traffic conditions. The observed convergence trends in waiting time, travel time, and cost optimization demonstrate the scalability and long-term effectiveness of the proposed approach. The system not only performs well initially but continues to refine its behavior as operating conditions evolve. This learning-oriented characteristic is particularly advantageous for smart building applications, where control systems are expected to adapt autonomously over time. Overall, the findings confirm that the proposed hybrid control framework offers a scalable, energy-efficient, and safety-enhancing solution suitable for next-generation smart buildings and high-rise elevator infrastructures.

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