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Real-Time Gain Scheduling via Adaptive Fuzzy PID Control: Application to Nonlinear Inverted Pendulum Stabilization

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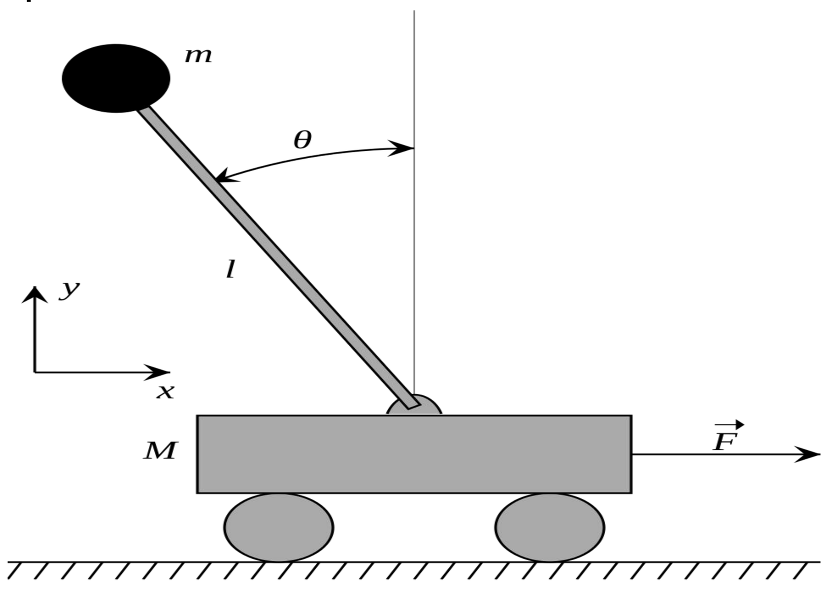
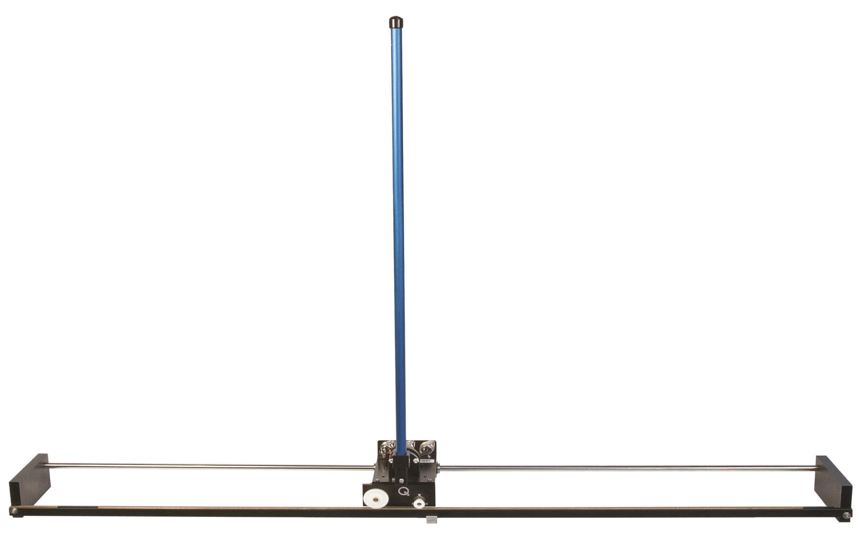
INTRODUCTION & AIM

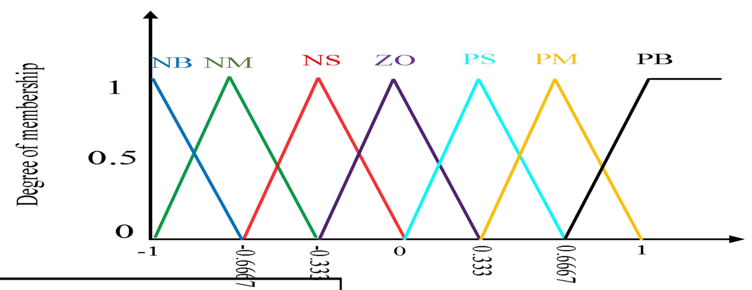
The control of nonlinear, unstable, and underactuated systems continues to be a major challenge in modern control engineering, and the inverted pendulum remains one of the most widely used benchmarks for evaluating advanced control strategies due to its inherent instability and strong nonlinear dynamics. Traditional PID controllers, although simple and widely adopted, typically lose effectiveness when exposed to parameter variations, disturbances, or modeling uncertainties because their fixed gains are tuned only for nominal conditions. Intelligent control methods, particularly those based on fuzzy logic, offer a promising alternative by exploiting rule-based reasoning and real-time adaptability without requiring a precise mathematical model. In this work, an Adaptive Fuzzy PID Controller (PIDFA) is developed to enhance classical PID performance by continuously adjusting the proportional, integral, and derivative gains according to the instantaneous system error and its rate of change. The aim of this study is to design and evaluate this adaptive controller for stabilizing the inverted pendulum, and to demonstrate its ability to provide fast convergence, effective disturbance rejection, and strong robustness under significant nonlinearities and parameter uncertainties.

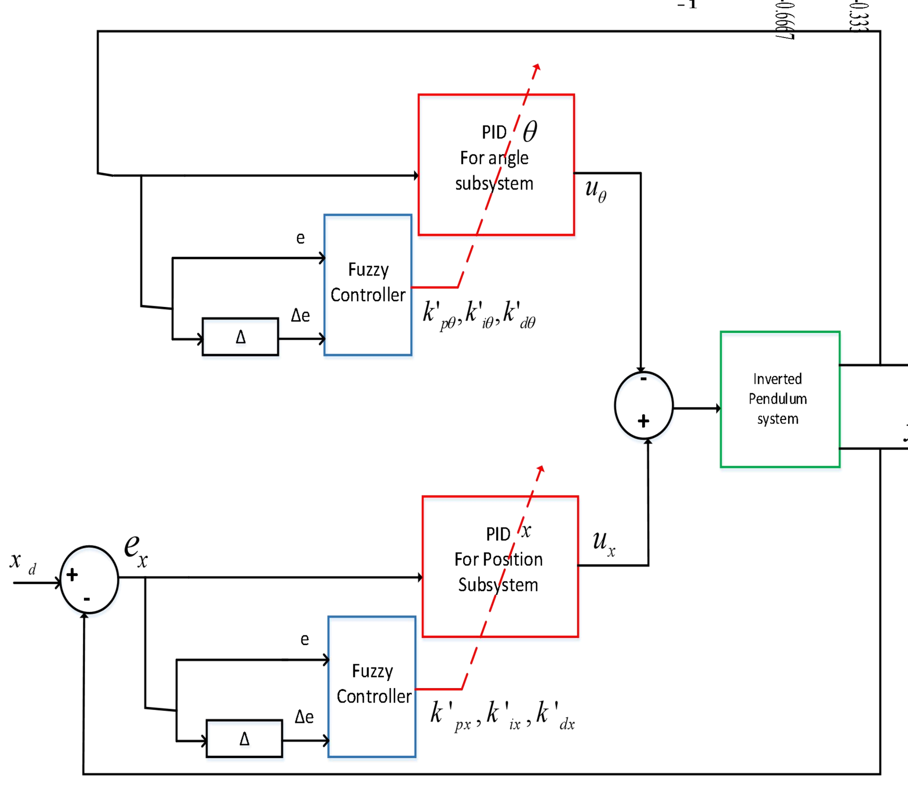


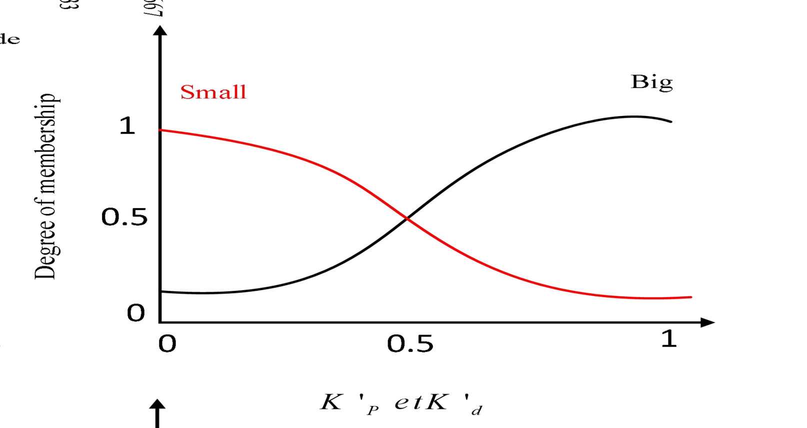


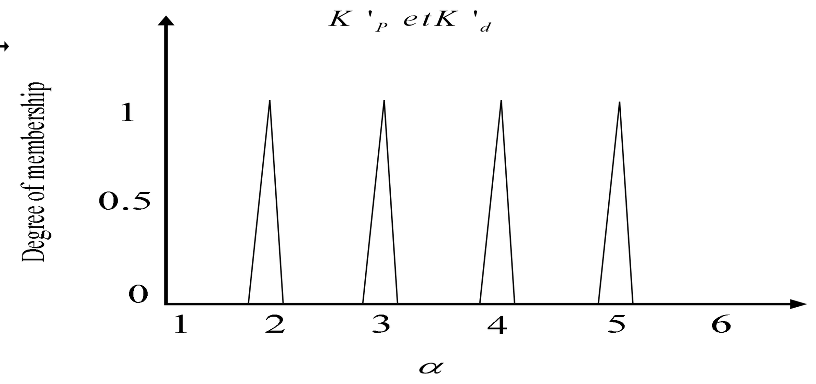
METHOD

The methodology followed in this study begins with modeling the inverted pendulum system using the Euler–Lagrange approach to capture its nonlinear and unstable dynamics, including the interaction between the cart motion and pendulum rotation. This model provides the basis for designing and testing the controller. The Adaptive Fuzzy PID Controller (PIDFA) is then developed by selecting the system error and its rate of change as the inputs to a fuzzy inference system, while the normalized proportional and derivative gains, along with an integral scaling factor, serve as the outputs. The fuzzy system uses triangular and trapezoidal membership functions for the inputs and Gaussian or discrete membership functions for the outputs, allowing smooth and interpretable gain adaptation. Three rule tables containing 49 fuzzy rules each define how the controller parameters should evolve in real time, enabling the gains to increase when the system deviates significantly and decrease as it approaches the upright equilibrium. The normalized gains are then converted into real PID gains through bounded linear transformations to ensure stable, continuous adaptation. The entire controller is implemented and tested in MATLAB/Simulink, where its performance is evaluated through stabilization tests, responses to sudden disturbances, and robustness assessments under changes in system parameters.



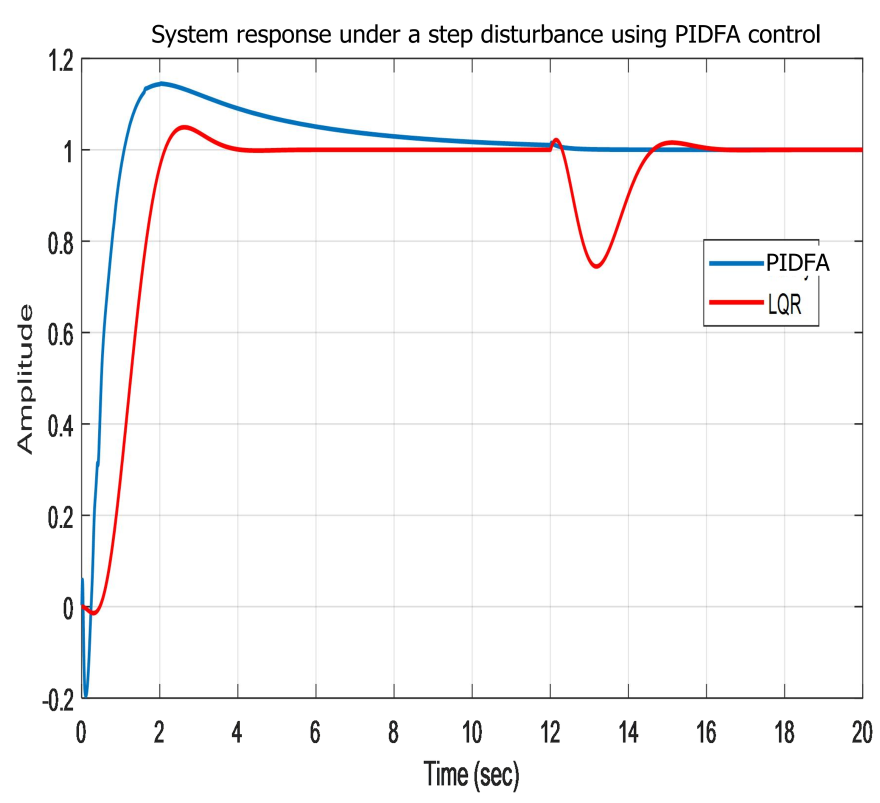


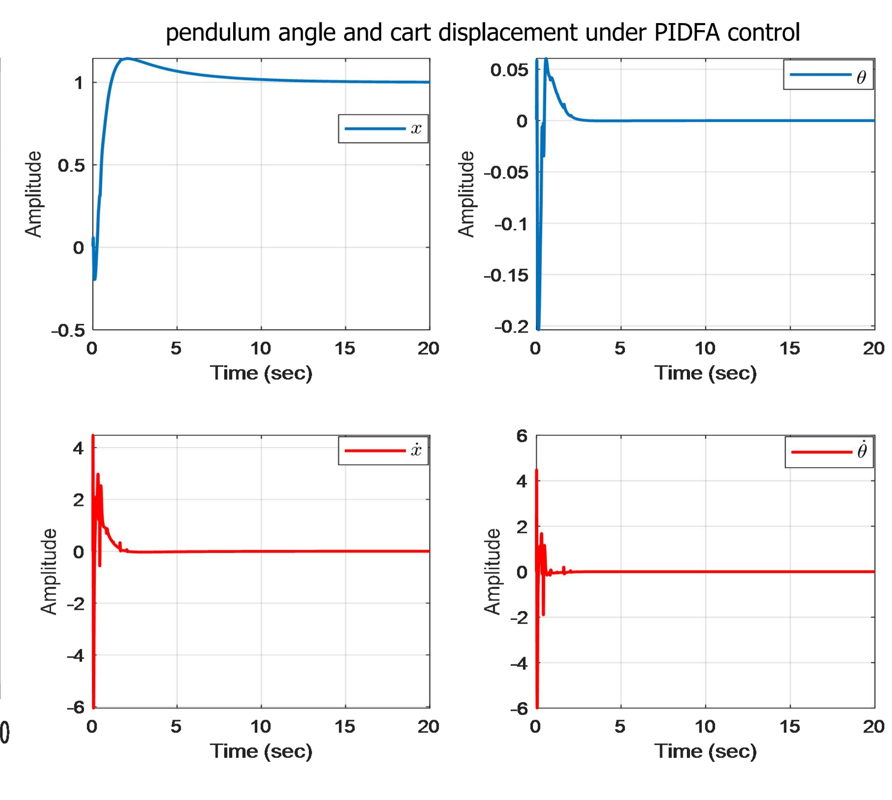




RESULTS & DISCUSSION

The simulation results demonstrate that the Adaptive Fuzzy PID Controller (PIDFA) provides strong stabilization performance for the inverted pendulum across a range of scenarios. Starting from an initial deviation near the unstable upright position, the controller dynamically adjusts its gains based on the instantaneous error and its derivative. This adaptive tuning allows the system to reach equilibrium within approximately 1.5–1.8 seconds, with minimal overshoot and no oscillatory behavior. The smooth transient response highlights the advantage of the fuzzy gain-scheduling mechanism, which increases the controller aggressiveness when the deviation is large while reducing it near equilibrium to avoid instability. This behavior contrasts with conventional fixed-gain PID controllers, which often struggle to achieve similar performance under nonlinear conditions without extensive manual tuning.Disturbance rejection tests further validate the robustness of the proposed approach. When a step disturbance is introduced at t =12 seconds, the PIDFA reacts immediately, modifying its gains in real time to counter the perturbation. Although a slight transient appears following the disturbance, the controller restores the pendulum to the upright position in less than 0.2 seconds. The system remains well-damped, without oscillations or performance degradation after the disturbance, demonstrating the controller's capability to handle unexpected dynamics.To evaluate robustness against parameter variations, the pendulum mass, cart mass, and pendulum length were deliberately modified. These changes emulate realistic uncertainties such as mechanical wear, load changes, or modeling inaccuracies. Despite these modifications, the PIDFA maintains stable and reliable performance without requiring any re-tuning or redesign of the controller. Only small changes in rise time and overshoot are observed, indicating that the adaptive fuzzy inference mechanism effectively compensates for the altered dynamics. Throughout all simulations, the control effort remains smooth and free from chattering or saturation, which is essential for practical implementation. These results collectively confirm that the PIDFA approach offers fast stabilization, strong disturbance rejection, and excellent robustness, making it a promising solution for real-time control of nonlinear and underactuated systems.





CONCLUSION

The Adaptive Fuzzy PID Controller (PIDFA) provides a powerful and practical approach for stabilizing nonlinear and unstable systems such as the inverted pendulum. By integrating fuzzy logic into PID gain scheduling, the controller responds intelligently to instantaneous system behavior and adapts its gains in real time.Simulations show excellent stabilization performance, fast recovery from disturbances, and strong robustness to parameter changes—significantly outperforming classical fixed-gain PID control.The fuzzy-adaptive structure makes PIDFA suitable for real-time applications where precise models are not available and operating conditions vary unpredictably. Future work includes hardware implementation, optimization of rule bases, and comparative studies with other intelligent controllers.