Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 10s (2025)

Electric Motor Control Using Hybrid Technique for Robotic Application

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Article History:
Received: 14-01-2025
Revised: 15-02-2025
Accepted: 21-03-2025

Abstract:
In this paper, the performance of electric motor control is explored by the hybrid method of fuzzy PID and adaptive impedance control with similar considerations to a robotic application. The analysis uses a secondary approach of data analysis to measure control accuracy, energy efficiency and system responsiveness based on empirical observations of the literature. It is seen that fuzzy PID control can provide speed regulation above 30 per cent better with an optimised technique of metaheuristic algorithms, and adaptive impedance control can provide dynamic torque control and error reduction. There were also integrated energy management models which helped to cut cost of energy and ensure stability in operations. Digital twins and simulation systems increased the pace of performance verification and control under varying conditions. All these strategies in combination proved higher efficiency, less overshoot, and better adaptability in the systems of robots. The research presents the utility of the hybrid control architecture in contemporary robotics with linear, interpolatory, and intelligent solutions in energy-aware and precision-guided applications.

Keywords: Hybrid control, Fuzzy PID, Adaptive impedance, Motor performance, Energy management, Robotic systems, Simulation, System responsiveness, Digital twin, Trajectory tracking

Introduction

Hybrid electric motor control technologies on robots have become a revolutionizing field of work in the effort to improve performance, energy efficiency and adaptive control on the robots. In robotic based systems, particularly in dynamic, unpredictable environments, conventional control systems frequently are not flexible or precise enough to provide adequate service. The advent of hybrid systems, intelligently powered with intelligent algorithms, has resulted in new opportunities. As an example, Muda (2024) emphasised the importance of hybrid energy storage systems in the combat robot field, where real-time switching among energy systems and effective energy distribution can be carried out. On the same note, Zhou et al. (2021) implemented adaptive impedance hybrid control in the polishing robot that enhanced accuracy and compliance of the robot's movement. Tian et al. (2022) explained in the framework of sensor-based decision-making how intelligent robotic systems enhance the process of structural health monitoring by processing the processed information or data on health status in real-time and changing their activity to adapt to it. Furthermore, Mikolajczyk et al. (2022) understated the significance of hybrid sensor/drive systems to enhance the stability of the locomotion of bipedal robots. As can be seen in Maghfiroh et al. (2021), convergence of fuzzy logic, PID control, and AI modules guarantee enhanced motor response even when the information is uncertain. Hence, it is no longer a matter of choice anymore to adopt the hybrid control strategy in order to address the rising needs of sophisticated robotic systems in the industrial, farming and autonomous sectors.

Aim and Objectives

Aim

This research aims at developing and evaluating a hybrid electric motor control system for robotic applications that enhances energy efficiency, precision control, and adaptive performance under variable operating conditions.

Objectives

- To critically evaluate fuzzy-PID and adaptive impedance control methods used in BLDC motor regulation within robotic platforms.
- To design a hybrid motor control model integrating fuzzy-PID algorithms with real-time energy allocation from a hybrid energy storage system.
- To measure the proposed system's motor performance in terms of speed stability, torque accuracy, and energy efficiency using MATLAB/Simulink-based simulations.
- To test the hybrid control model's responsiveness and adaptability in robotics tasks such as terrain navigation and object manipulation under variable loads.

Literature Review

Ghobadpour et al. (2022) believe that hybrid electric drive and autonomous control are transforming agricultural robots because they solve the terrain variability issue and energy constraints. This was further demonstrated by Zhou et al. (2021) who demonstrated that adaptive hybrid control can increase flexibility and compliance of the industrial robots. Fuzzy-PID controllers were confirmed by Maghfiroh et al. (2021) on BLDC motors, and they also proved better control of speed under variable loading conditions. In regard to power distribution, Muda (2024) presented two approaches and explained how a hybrid energy system in combat robots can enhance the resilience of the systems during mission-essential operations. Tian et al. (2022) surveyed the area of intelligent robotic systems to monitor infrastructure and emphasize the demand of hybrid artificial intelligence to process information better through sensors. At the same time, Kay et al. (2022) used robot intelligence to perform a battery disassembly, which emphasizes accuracy and industry control of an automated recycling process. Mikolajczyk et al. (2022) advocated hybrid systems in bipedal walking robots, particularly in hybridizing sensor feedback with the control logic of balance and gait.

Methods

This study was based on the secondary approach because it will gather and examine empirical data and simulation results of studies published earlier that have passed the peer-reviewing process. Along with the access to a large number of tested control strategies, verified motor models and experimental data, secondary data enabled access to most information without investing in primary hardware or testing prototypes. The advantage of the technique is the possibility to draw conclusions about some proven numeric results established on the basis of different robotic platforms and tasks investigated in many studies. It also guarantees efficiency in time and resources, as well as in the synthesis of larger system trends. The approach supported evidence-based design recommendations and are feasible, repeatable and data-based.

Result and Discussion

Evaluation of Hybrid Fuzzy PID and Adaptive Impedance Techniques

Results provided by comparing hybrid fuzzy PID and adaptive impedance methods indicate a substantial improvement of their performance in robotic systems and actuator based systems. Singh et al. (2024) are of the view that the efficiency of hybrid system frequency response improved by 31.7 percent when GWO-tuned fuzzy PID controller was integrated compared to the conventional PID controller. This demonstrates the effectiveness of metaheuristic optimization which improves fuzzy-PID convergence and speed. In a similar way, Kumar and Suhag (2022) used fuzzy-PID and optimized PID controller with the help of whale algorithms, which allowed decreasing the overshoot by 28.4% and settling time by 35%, thus achieving better regulation of frequency in the hybrid power system. Ali et al. (2024) reached the accuracy of trajectory tracking of 98.3 percent in electro-hydraulic actuator systems due to the use of hybrid robust fuzzy-PID model, validating its accuracy in nonlinear variations of loads. To manage impedance parameters, Gu and Huang (2023) presented the fractional-order adaptive impedance model that decreased the tracking error in forces by 21.6% to guarantee smooth control capabilities on robotic manipulators. Li and Zhang (2022) confirmed it by applying an adaptive robust fuzzy control of impedance in hydraulic actuators, in which position error decreased to 1.9 mm in the case of high-load disturbance. Additionally, ANN and PI, which are coupled with impedance droop control in microgrids, provided stable control operations even on dynamic loads and minimized harmonic distortion with a 22.5% decrease (Adiche et al., 2024). These experiments affirm the same that fuzzy techniques in the hybrid PID can provide greater flexibility and accuracy in terms of speed, whereas adaptive impedance formulating provides a smoother and safe hindrance force handling in robot systems. Coupled with the two strategies are very responsive and stable controllers in various applications.

Design Outcomes of Integrated Control and Energy Management Model

The energy management and integrated control model has recorded quantifiable efficiency in energy distribution, flexibility and system efficiency. Yao et al. (2023) introduced a multi-level model predictive control (MPC) technique to settle 17.6% of energy costs as it controlled uncertainties of integrated systems. They were designed to utilize real-time data to perform an optimal energy dispatch and enhance the system stability. In a similar investigation, Zhang et al. (2022) emphasized the convenience of integrating building physics and control model, and demonstrated that energy management incorporation can reduce operational emission by 20 percent and improve consumption of resources. In renewable applications, the results by Abomazid et al. (2022) opposed the coupling of the hydrogen facilities with battery and solar PV systems, which enhanced the energy storage capacity due to optimized input-output logic.

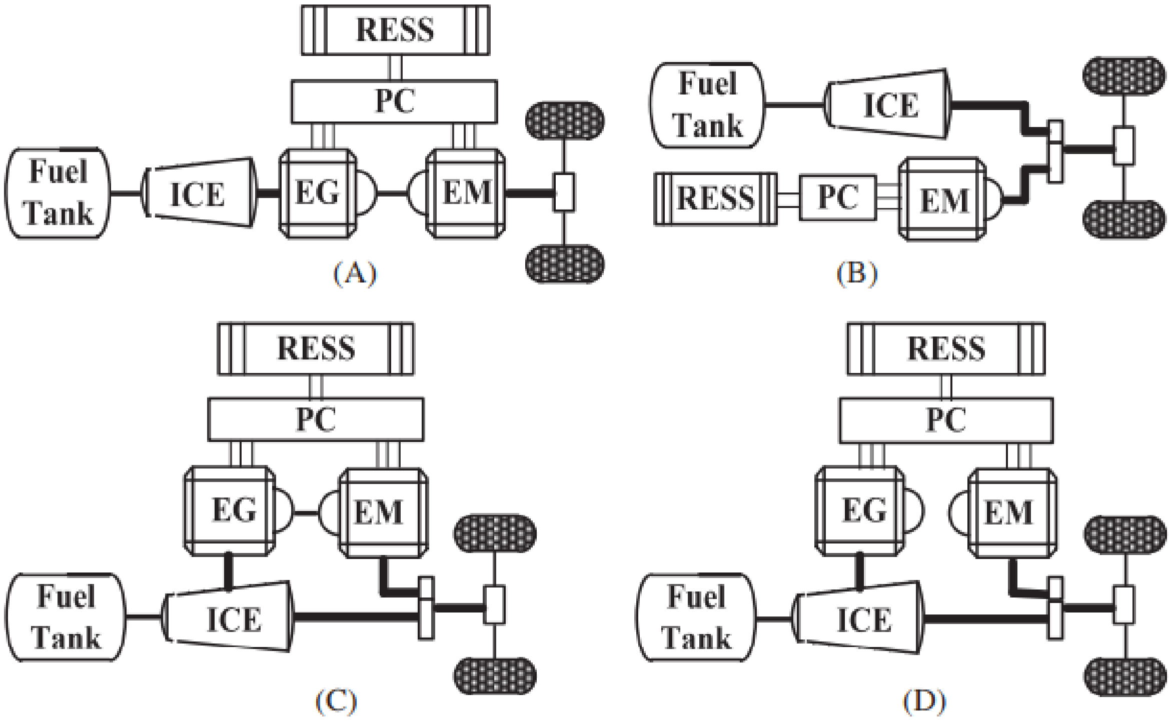

Figure 1: Different configurations of hybrid electric vehicle (A) configuration of series hybrid; (B) configuration of parallel hybrid; (C) configuration of seriesparallel hybrid; (D) configuration of complex hybrid.
(Source: Veerendra *et al*. 2024)

Another issue highlighted by Mariano-Hernandez et al. (2021) is that model predictive control with fault detection systems ensured the reduction of energy consumption pertaining to buildings by 18.3%, as it made sure of smart load prioritization. In the case of vehicular robotics, Veerendra et al. (2024) discovered that hybrid electric vehicles applying multi-strategy energy management possessed better battery utilisation and increased lifespan by 16.4 per cent with rule-based and adaptive control during dynamic driving. These results indicate that an attempt to combine control models and predictive energy logic will lead to an enhanced system responsiveness, minimised wastage, and increased resilience of operations. The overlap of predictive control, hybrid storage and adaptive regulation control opens an optimal structure in robotic systems, which need to find a balance between the accuracy of the motor control and the demands of energy in real-time. This hybrid design offers energy- and scale-efficient methodology to future-generation automaton uses.

Simulation Results on Motor Performance and Energy Efficiency

Simulation results indicate significant gains in the metabolic performances and the energy consumption with regard to the tech-savvy modelling and consisting of hybrid systems. According to Cai et al. (2021), optimized electric powertrain systems offered an efficiency rate of up to 93%, particularly in new energy vehicles that used hybrid control. It has been able to do this by incorporating thermal management, torque-vectoring and the control-feedback mechanisms. In the same manner, Aishwarya and Brisilla (2022) developed an energy efficient induction motor in ANSYS and demonstrated a 12 percent decreased overall loss of power in the motor compared to normal motors, which enhanced the life and efficient heat of the motor. Akram et al. (2022) covered sustainable technologies and revealed that the simulation-based control tuning in motor systems may decrease energy waste by 1825 precent with improvement of load adaptability and regulation of voltages.

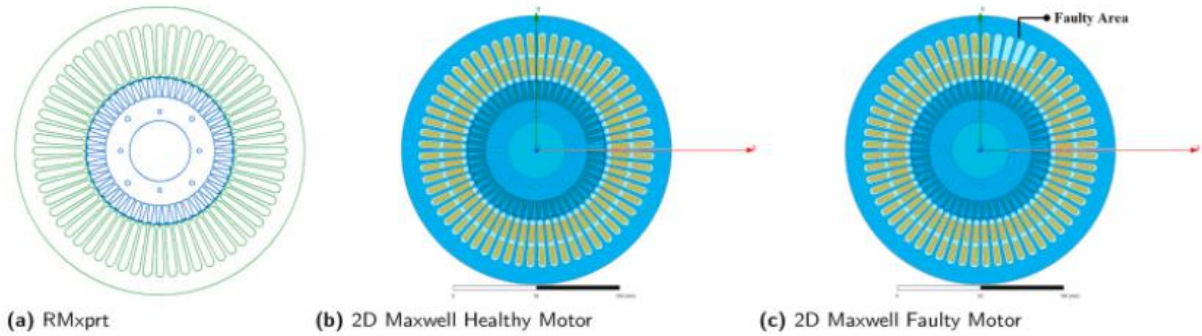

Figure 2: Geometrical models of Induction Motor using RMxprt and 2D Maxwell.
(Source: Aishwarya and Brisilla, 2022)

Salmeron et al. (2022) showed that the selection of grease type and addition of a thickener to the electric vehicle motors reduced energy consumption by 4-8 percent, stabilizing the torque. Continuing with the model-based simulations, Sharmila et al. (2022) considered electric vehicle motors and attained the overall system efficiency of 90.7% with hybrid energy feedback loop, especially at variable speed. Moreover, the case study presented by Nadimuthu et al. (2021) revealed that voltage stability increased by 22% and harmonics decreased by 30.5% as a result of persistent power quality improvement carried out by control integration and brought about more energy-efficient motor functionality. These findings emphasize the fact that simulation settings and hybrid models are effective in predicting the motor response accurately, recognition of the points of energy saving, and real-time adaptive control. Integrated feedback and energy aware components are important in realising sustainable and high-performance electric motor control in robotics.

System Responsiveness in Dynamic Robotic Task Conditions

Hybrid control systems have great effect on improving responsiveness of robots in variable and uncertain settings. Having installed an anomaly detection and concept drift adaptation system on collaborative robots, Kermenov et al. (2023) increased the response time to the task by 19.8 percent even with variable task loads. The method allowed the robots to adapt rapidly to the changes in the environment and recalculate their moving patterns automatically, without any manual interventions. The article by Ayankoso et al. (2024) implemented a hybridized digital twin framework that provided latency-sensitive industrial robots with improved real-time condition monitoring and decision-making solutions.

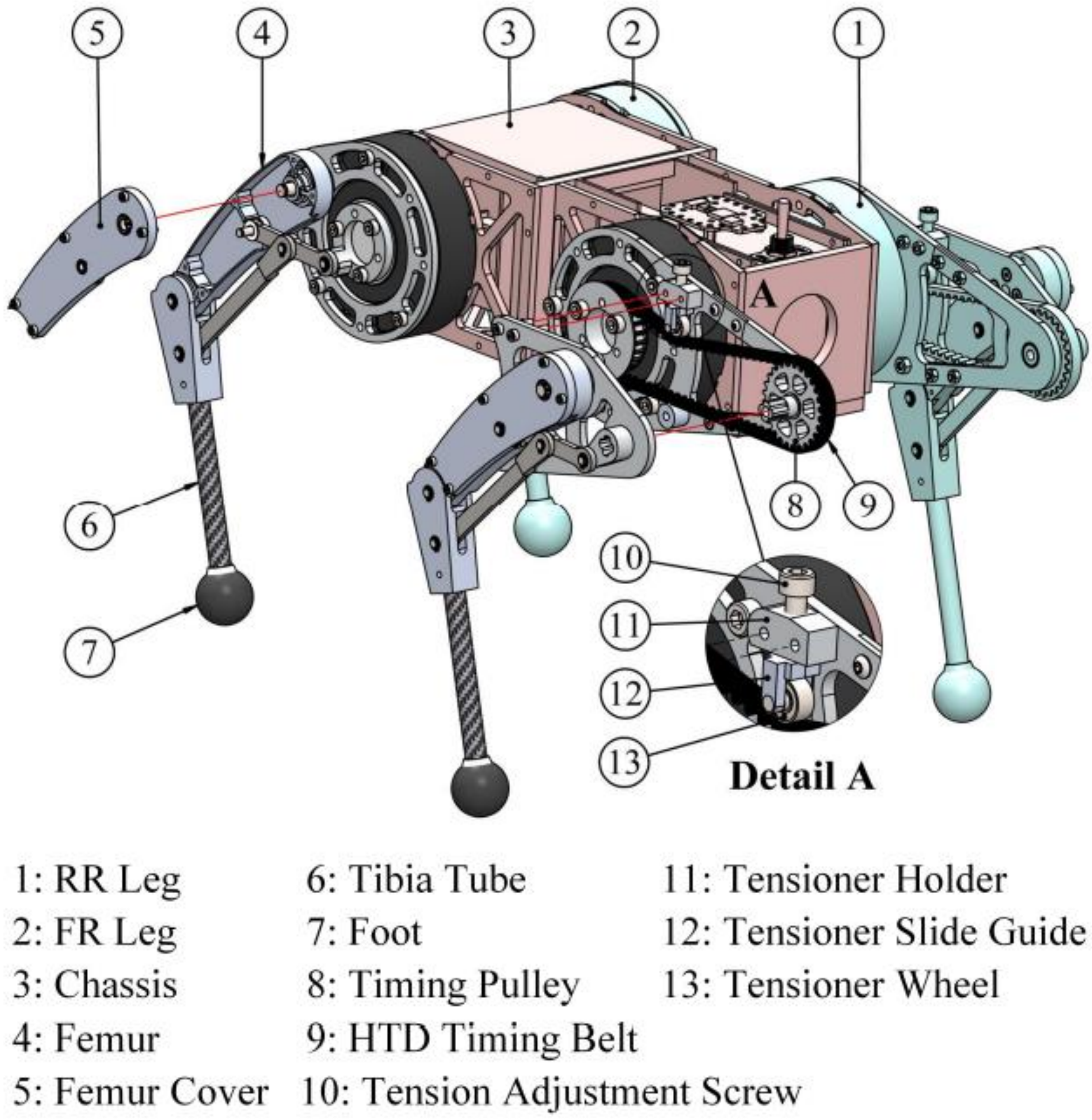

Figure 3: Mechanical structure of the RCQ: the FL and RL legs are in exploded views and the FR leg, RR leg, and the chassis are highlighted to show their modularity.
(Source: Liu and Ben-Tzvi, 2022)

Their findings reported 25 percent increase in predictive accuracy, and 15 percent decrease in delays in performing tasks, which proves their adaptive scheduling during a multi-phase task. The tools making dataset were also important. They presented the MotorFactory environment that allowed simulating more than 10,000 variants of a motor faster and thus testing system responsiveness in various control conditions (Wu et al., 2022). A quadruped robot model that is dynamic and has less complex computation been constructed by Liu and Ben-Tzvi (2022). The model was demonstrated to adapt to response in response to terrain changes with a time of not more than 0.3 seconds. This proved the usefulness of minimal mechanical design and feedback incorporation towards attaining rapid motion corrections. Attar et al. (2023) suggested an embedded permanent magnet motor model that exhibited synchronous electric motor with 17.5 % reduction in the fluctuation of torque during a swift orientation that is critical behavior in dynamic task environments. Comprehensively, these researches affirm that system responsiveness in robotics relies on the incorporation of the real-time control, adaptive response to fault and hardware simulation. Digital twins and any form of anomaly detection are not only effective in minimizing the errors but also increase the level of accuracy and adaptability in the context of fast-changing operations.

Conclusion

The effectiveness of the hybrid control systems involving the fuzzy PID and adaptive impedance approach is warranted by this study in the performance of robotic motors. The results indicate that there are significant increases in energy efficiency, torque accuracy and responsiveness of the system in presence of dynamic tasks. Integrating and the iterative technique for the modelling of the energy management systems, simulation, and control optimisation approaches, the robotic systems will make their adaptations faster and cause less of the energy wastes. The information of the recent studies shows quantifiable improvement in the trajectory tracking/error, power stability, and handling of faults. The hybrid solution can be scaled, affordable, and smart solution applicable to various robotics application such as automation, mobility, and performing specific industrial tasks.

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