engineering proceedings

MDPI

Conference Report

Abstracts of the 3rd International Electronic Conference on Machines and Applications, 12–14 May 2026 †

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† All abstracts are accepted by the 3rd International Electronic Conference on Machines and Applications, 12–14 May 2026; Available online: https://sciforum.net/event/IECMA2026.

Keywords: machines; automation; monitoring; fault diagnosis; additive manufacturing; energy conversion; mechatronics

1. Automation and Control Systems

1.1. Automated Machine Systems for Monitoring Plant Growth and Physiological Stress

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Automated machine systems play a critical role in plant biology by enabling precise and continuous monitoring of growth and physiological stress under varying environmental conditions. This study presents a systematic evaluation of previously developed machine architectures integrating mechanical positioning units, optical and environmental sensors, and automated data acquisition platforms for high-throughput plant phenotyping. Configurations for measuring morphological traits and physiological indicators, such as leaf area, chlorophyll concentration, and water status, are critically analyzed based on insights from published studies. The performance of these systems is assessed in terms of measurement accuracy, repeatability, adaptability to dynamic plant growth, and sensitivity to environmental fluctuations. Key challenges related to mechanical precision, sensor calibration, and long-term operational stability are discussed. While existing systems provide valuable understanding of plant responses, limitations remain in scalability, adaptability across species, and integration under variable environmental conditions. Based on this evaluation, original perspectives are proposed for next-generation automated monitoring platforms, emphasizing modular mechanical design, adaptive sensor fusion, and intelligent data-processing algorithms. Integration of real-time feedback and machine-learning-based anomaly detection is highlighted as a promising approach for early identification of physiological stress and optimization of growth conditions. This work highlights the significance of engineering-driven machine solutions in biological monitoring and provides a conceptual framework synthesizing insights from current technological developments, guiding interdisciplinary research at the interface of automation, mechatronic systems, and plant biology.

1.2. Performance Evaluation of OPC UA PubSub Implementation for ESP32 Microcontrollers in Local and Cloud Environments

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Academic Editor: Niccolò Grossi

Published: 16 July 2026

The integration of legacy industrial assets into IIoT frameworks requires standardized protocols compatible with resource-constrained hardware. This paper evaluates an implementation of the OPC UA PubSub protocol (IEC 62541-14) developed in MicroPython for an ESP32 microcontroller, addressing the challenge of deploying industrial communication standards on low-cost embedded platforms. This research benchmarks the protocol stack's performance through systematic 50-sample statistical analysis, comparing local and cloud MQTT broker deployments. The methodology isolates protocol processing overhead from network infrastructure effects, enabling the precise characterization of implementation efficiency. The results demonstrate a deterministic internal serialization time of 8.46 ms ($\pm$1.26 ms), which remains invariant regardless of network infrastructure, validating the protocol's computational stability. The library maintains a minimal memory footprint, with a peak consumption of only 4.86 KB per message cycle. Network performance analysis revealed significant differences between deployment scenarios. Local broker deployment achieved an average RTT of 119.71 ms with a jitter of 111.37 ms, while cloud broker deployment exhibited an RTT of 985.36 ms with a jitter of 206.49 ms. Despite the 8.2$\times$ latency increase in cloud scenarios, the system maintained a 100% message delivery success rate without packet loss across all test conditions. This study concludes that this implementation provides a robust foundation for industrial telemetry and monitoring applications in brownfield scenarios, demonstrating resilience under varying network conditions while maintaining strict protocol compliance with IEC 62541-14.

1.3. The Role of Society in Waste Supply Chain Simulation

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Within the contemporary paradigm of escalating intricacy within waste supply chains, the utilization of simulation as a modeling instrument for existing processes within supply chains has assumed a pivotal role. This instrument is utilized for the analysis and generation of scenarios, with the objective of predicting results and performance indicators in terms of sustainability. Nevertheless, a plethora of studies concentrate on the reduction of costs and collection and treatment times, emphasizing operational and logistical performance, while human behavior is regarded as a constant variable. However, this approach is not without its limitations, particularly when it comes to the applicability of models in real-life settings. In such contexts, it becomes imperative to incorporate societal behaviors, such as adherence to sustainable policies, into the modeling process. It is therefore crucial to make the model dynamic and more realistic. The present article thus aims primarily to examine the societal contribution to the simulation of waste supply chains through a literature review of concepts such as the role of society in sustainability and simulation. Subsequently, a quantitative and qualitative analysis was performed using the Scopus database. The results of the study indicate that a mere 6% of the documents under review are associated with the social dimension of sustainability, a figure that is clearly insufficient given the importance of the social dimension. It is recommended that further studies be conducted in order to apply this dimension of sustainability to simulation, with a view to obtaining more complex and robust models and, consequently, more accurate results.

1.4. A Decentralized Swarm Intelligence Algorithm for Resilient UAV Coordination in Environmental Monitoring: A Python Simulation and Performance Analysis

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The coordination of Unmanned Aerial Vehicle (UAV) swarms for environmental monitoring faces significant challenges due to the limitations of centralized control, including single points of failure and high communication latency in dynamic environments. This study addresses the need for robust, scalable, and adaptive coordination without relying on a central controller. Methods: We propose a decentralized swarm intelligence algorithm based on local interaction rules, including separation, alignment, and cohesion, to govern collective agent behavior. The model was implemented and validated using a custom Python simulation environment, focusing on formal stability metrics that link local agent rules to global swarm dynamics. Results: Performance analysis using Swarm Performance Indicators (SPIs) demonstrates that the decentralized approach ensures high swarm stability and resilient network connectivity. Quantitative evaluations show that the system maintains operational integrity even under partial agent failure, outperforming traditional centralized architectures in scalability and fault tolerance. Specifically, the algorithm optimizes the trade-off between tracking accuracy and communication link quality, maintaining stable coordination with linear computational complexity. Conclusions: The findings highlight the efficacy of decentralized algorithms for enhancing the autonomy and resilience of mechatronic systems. This research provides a scalable analytical framework for next-generation autonomous systems in complex monitoring tasks, directly contributing to the field of automation and machine design.

1.5. A Decision Framework to Select Robotics Simulators for Automation and Control Tasks: Criteria and Validation

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Robotics simulation is a key enabler for automation and control development, allowing safer experimentation, faster design iterations, and reduced development cost. Nevertheless, the current simulator ecosystem is highly fragmented, spanning open-source and commercial tools with different levels of physical fidelity, performance, and ecosystem integration. As a result, simulator selection is frequently driven by familiarity or availability rather than explicit task requirements, often leading to suboptimal engineering workflows. This paper proposes a task-oriented decision framework to support reproducible and transparent selection of robotics simulators based on a fixed and structured set of evaluation criteria. These criteria cover: (i) physical fidelity and contact modeling; (ii) sensor modeling and visual realism; (iii) performance and scalability aspects, including headless execution, parallelism, and GPU acceleration; (iv) ecosystem integration with automation, control, and learning pipelines, including ROS/ROS 2 compatibility; (v) extensibility and programmability; and (vi) practical constraints such as hardware requirements, licensing models, and learning curve. The framework is operationalized through a checklist and scoring matrix guided by four key questions addressing the target task, fidelity-versus-speed priorities, target software stack, and sim-to-real transfer requirements. To validate feasibility in a representative engineering workflow, a URDF-based modeling and simulation pipeline is implemented and used to compare Gazebo, as an open-source physics-based simulator, against MATLAB/Simulink, representing a commercial model-based simulation environment. The comparison reports practical indicators, including setup effort, integration complexity, computational requirements, and runtime behavior, for representative motion and sensing scenarios. The results highlight consistent trade-offs across different user profiles and application needs, while also revealing open gaps in the field, notably the lack of unified multi-task benchmarks and joint metrics capable of simultaneously capturing simulation fidelity, computational performance, and sim-to-real transfer effectiveness.

1.6. A Low-Cost Arduino Validation of a Nonlinear Control Technique for a Standalone Photovoltaic System

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The rapidly increasing demand for standalone photovoltaic (PV) system deployment requires not only highly efficient control methods under rapidly changing environmental conditions but also methods that are economically affordable for real-world applications. In the PV field, conventional techniques may fail in the face of these significant challenging events, making their practical execution on low-cost hardware boards demanding. This study investigates the real-time implementation feasibility of a Nonlinear Backstepping Control (NBC) method for a standalone PV system, using an Arduino Due platform, within MATLAB/Simulink software. The applied system integrates a PV generator based on Kyocera 200GT (KC200GT) modules, linked to a DC–DC boost converter supplying a DC load. The proposed Maximum Power Point Tracking (MPPT) ensures stable, controlled extraction of the PV power under abrupt atmospheric conditions. The obtained results demonstrate a superior tracking efficiency that exceeds 97%, without exhibiting significant oscillations. In contrast to classic control strategies such as Perturb & Observe (P&O), which produce high fluctuations, leading to poor MPPT efficiency, especially under Standard Test Conditions (STC), the Arduino-in-the-loop evaluation of this nonlinear technique establishes high consistency between embedded and simulation results, indicating its superior accuracy, rapid convergence, and smooth power extraction, showing its suitability for real-world standalone PV system applications under cost-effective embedded systems.

1.7. A Methodological Survey of Autonomous Mobile Robots and Automated Guided Vehicles in Industrial Logistics

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Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs) are among the key enabling technologies driving intelligent logistics and industrial automation. Despite their widespread adoption and rapid technological evolution, the literature often addresses AGV and AMR systems in a fragmented manner, lacking a structured methodological perspective that highlights their architectural foundations, levels of autonomy, and technological maturity. This paper presents a methodological survey of AGV and AMR technologies, focusing on system-level architectures and core functional components rather than isolated algorithms. The survey systematically analyzes key technological dimensions, including sensing and perception, localization and positioning strategies, navigation and path-planning approaches, communication infrastructures, and multi-robot coordination mechanisms. A clear distinction is drawn between classical AGV systems, which rely on fixed infrastructure and predefined routes, and AMR systems, which exhibit adaptive, perception-driven, and self-configuring behaviors enabled by artificial intelligence techniques. Rather than proposing new algorithms, this paper organizes existing approaches into a coherent framework that highlights technological transitions from infrastructure-dependent guidance to autonomous, data-driven navigation. Recent trends such as cloud–edge integration, learning-based navigation, scalable fleet management architectures, and cooperative multi-robot systems are reviewed and discussed from a methodological standpoint, emphasizing their role in increasing flexibility, robustness, and operational efficiency in industrial and logistics environments. The survey also addresses cross-cutting challenges, including system transparency, safety and certification, interoperability, and sustainability. Finally, the paper outlines research directions aligned with the principles of Industry 5.0, highlighting the need for human-centered, resilient, and scalable AMR and AGV systems capable of safe and explainable operation in complex industrial contexts.

1.8. Adaptive Path Planning for Drone-Based Construction Site Inspection Using Fractal Image Processing and Deep Learning

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Drone-based inspection has become an effective tool for improving safety and efficiency in construction applications; however, designing flight paths that balance coverage, inspection resolution, and limited flight time remains challenging. Conventional path planning approaches typically apply uniform flight patterns and fixed image resolutions across entire construction sites, leading to redundant scanning in low-complexity areas and insufficient inspection of critical regions. This paper presents an adaptive drone path planning framework for construction applications that integrates fractal image processing with deep learning-based hazard detection.

The proposed approach first captures a preliminary image of the construction site and applies a fractal quadtree algorithm to partition the site into regions of varying spatial resolution based on visual complexity. These partitions are clustered into multiple

https://doi.org/10.3390/engproc2026145006

altitude levels, enabling resolution-aware path planning in which drones are deployed at different heights to efficiently inspect regions with distinct complexity requirements. High-complexity areas are assigned finer resolutions and lower flight altitudes, while low-complexity areas are inspected at coarser resolutions from higher altitudes.

To enable automated safety inspection, a YOLO-based deep learning model is employed to identify construction hazards from images captured by drone-mounted cameras. The detection model is trained offline using labeled construction site imagery and is capable of recognizing multiple hazard types under varying environmental conditions. Simulation results using real construction site images demonstrate that the proposed method significantly reduces the number of required scan locations compared to traditional random walk and zigzag flight patterns while maintaining sufficient image quality for reliable hazard detection. The proposed framework provides an efficient and scalable solution for adaptive drone-based construction site inspection.

1.9. AI-Powered Computer Vision Industrial Quality Inspection Systems: A Practice Review

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Computer vision (CV) systems driven by artificial intelligence (AI) are gradually replacing manual, real-time, and data-driven processes in industrial quality inspection, enabling automated decision-making based on visual data. Conventional inspection procedures are usually limited in terms of scalability, human-related errors, and high operational costs, which drives the increasing reliance on smart vision-based technologies. A practical, practice-oriented review of AI-based computer vision systems for industrial quality control is provided in this paper, with emphasis on real-world deployment issues and performance aspects. Two representative industrial case studies are examined. The first investigates the use of real-time extrusion monitoring in robotic building construction, where geometric deviations, surface defects, and process inconsistencies are detected during material deposition using deep learning-based vision models. The second case study focuses on automated inspection of bolts and screws in manufacturing lines, addressing presence detection, orientation recognition, and defect classification under high-speed production conditions. In both cases, widely adopted AI techniques, including convolutional neural networks, image processing pipelines, and edge-computing hardware, are discussed and compared. The analysis shows that AI-enabled computer vision systems significantly outperform traditional rule-based or manual solutions in terms of inspection accuracy, consistency, and throughput. Nevertheless, challenges related to dataset quality, model generalization, lighting variability, and real-time computational constraints remain critical in industrial environments. In conclusion, AI-based computer vision plays a central enabling role in intelligent quality inspection within the context of Industry 5.0. Future research should focus on adaptive model capabilities, tighter integration with cyber-physical systems, and scalable deployment strategies to achieve reliable and autonomous inspection across diverse industrial sectors.

https://doi.org/10.3390/engproc2026145006

1.10. An Embedded Vision-Based Autonomous System for Converting Hand-Drawn Glass Sketches into Engraved Objects

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This paper presents an embedded vision-based autonomous system designed to convert hand-drawn sketches created on a transparent glass surface into engraved or cut patterns on solid materials such as wood and plastic. The proposed machine aims to simplify human–machine interaction in digital fabrication by enabling users to draw naturally by hand without requiring a computer, display, or specialized software interface.

The system integrates a glass-based drawing surface positioned above an embedded camera that captures the user's sketch from below. The acquired image is processed locally on a Raspberry Pi, where embedded image processing algorithms are applied to extract contours and geometric features from the hand-drawn sketch. The extracted paths are then converted into standard G-code instructions, ensuring compatibility with conventional CNC motion control principles.

The generated G-code is executed directly by a dedicated mechatronic platform consisting of a Cartesian motion system driven by stepper motors. To ensure positional accuracy and repeatability, a reference positioning sensor is employed to define consistent machine origin prior to each operation. After pressing a single physical start button, the system autonomously reproduces the original hand-drawn sketch as an engraved or cut pattern on the target material without further user intervention.

Unlike conventional CNC or laser engraving systems that depend on external computers and complex graphical interfaces, the proposed solution emphasizes autonomy, usability, and compact system integration. Experimental results demonstrate reliable reproduction of complex hand-drawn shapes with stable motion behavior and repeatable positioning accuracy.

The proposed approach is particularly suitable for educational environments, artistic fabrication, and low-cost rapid prototyping applications, and highlights the potential of embedded vision and autonomous mechatronic systems in human-centered manufacturing workflows.

1.11. An ESP32-CAM Embedded Data Infrastructure for Database-Driven Emotion-Based Student Readiness Assessment

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This work proposes an embedded data infrastructure based on ESP32 microcontrollers integrated with ESP32-CAM modules, focusing on the construction, management, and utilization of a centralized facial image database for emotion-based student readiness assessment. In the proposed architecture, multiple ESP32-CAM devices operate as distributed embedded sensing nodes, capturing facial images of students during academic assessment activities. Each embedded node performs lightweight preprocessing tasks, including image resizing and noise reduction, to optimize transmission efficiency and reduce network load. The preprocessed images are transmitted via Wi-Fi to a centralized database system, where they are securely stored and indexed for subsequent analysis. The database serves as a core component for large-scale data organization, enabling automated processing, historical tracking, and statistical aggregation of emotional data. A convolutional neural network (CNN), trained on the FER2013 dataset, analyzes the stored images to infer facial emotion categories, which are subsequently mapped to quantitative indicators of concentration and nervousness. This separation of embedded data acquisition from centralized analysis allows improved scalability, efficient resource utilization, and flexibility for future model updates without modifications to the embedded hardware. Experimental results demonstrate that the ESP32-CAM platform provides reliable long-term operation and consistent image quality in classroom-like environments. The proposed architecture highlights the role of embedded systems not only as data acquisition devices but as fundamental components of data-centric, emotion-aware educational platforms.

1.12. An Integrated Automation Framework for Monitoring and Control of Material Processes

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The automation of material receiving processes plays a central role in ensuring traceability, process control, and data consistency in warehouse and logistics environments. Inbound material registration is a critical stage, as inaccuracies at this point propagate throughout subsequent operational processes. This paper presents an integrated automation framework focused on the monitoring and control of material entry processes, emphasizing structured data acquisition and system-level control. The proposed framework is composed of a mobile application designed for material intake registration and a centralized web-based platform responsible for data storage, validation, and monitoring. The inbound application supports the capture of material information through document scanning, image recording, and structured input fields, while the web platform consolidates records, enables historical tracking, and manages access and device control. From a methodological perspective, the system architecture was developed based on automation and control principles, with emphasis on modularity, process standardization, and consistency of information flow. The framework enables real-time registration of inbound events and continuous monitoring of material entry status through a centralized interface. Experimental deployment in a controlled warehouse scenario demonstrated the system's ability to ensure coherent registration of inbound materials, reduce information gaps during receiving operations, and support traceability through structured data records. The results indicate that the proposed framework provides a consistent and controllable approach to inbound material monitoring. From a theoretical standpoint, the study contributes to the understanding of automation-oriented system architectures for material entry processes, offering a reference model for future developments in warehouse automation and control systems.

1.13. Automated Dimensional and Geometric Inspection of Metal Plates Using a Collaborative SCARA Robot: A Preliminary Proof-of-Concept Study

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Industrial manufacturing increasingly requires reliable and repeatable dimensional and geometric inspection of small metal components, while minimizing inspection time, operational cost, and operator dependency. Conventional manual inspection based on mechanical fixtures remains widely used but is limited by operator variability, reduced flexibility, and poor scalability in high-mix production environments. This work presents a preliminary proof-of-concept for an automated dimensional and geometric inspection system based on a collaborative SCARA robot, whose primary role is to ensure repeatable positioning, handling, and automation of the inspection process. At this stage, the industrial problem is intentionally simplified to a representative squared tubular metal plate, preserving key length and width requirements while postponing full three-dimensional profile verification to later development phases. This incremental strategy reduces technical risk while enabling early validation of referencing, repeatability, and automated cycle execution. Rather than committing to a single measurement technology, the proposed system architecture remains measurement-agnostic, allowing the integration of different inspection approaches, such as vision-based methods, dedicated mechanical gauges, contact or non-contact sensors, and instrumented fixtures. In this context, the robot enables the automated manipulation and placement of parts into predefined inspection setups, replacing manual handling while preserving measurement reliability. A structured analysis of functional and operational requirements is used to justify this flexible architecture and to highlight its potential economic and operational benefits. Virtual validation is carried out using MATLAB-based simulation tools, namely Simulink 3D Animation and Simscape Multibody, to assess system layout, robot motion, accessibility, and cycle execution prior to physical integration. The results demonstrate the feasibility of the proposed concept and support a phased roadmap towards more advanced geometric inspection capabilities in subsequent development stages.

1.14. Benchmarking Classical and Predictive Control Strategies for AMR/AGV Systems Using a Modular MATLAB Framework

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The use of Autonomous Mobile Robots (AMRs) and Automated Guided Vehicles (AGVs) is increasingly relevant in industrial and logistics environments, particularly during the early stages of system development, where control, navigation, and coordination strategies must be evaluated efficiently and have low implementation overhead. This paper presents a modular and transparent MATLAB-based simulation framework designed to support early-stage modeling, comparison, and validation of AMR/AGV behaviors under realistic operational conditions. The proposed framework is implemented exclusively in base MATLAB, without relying on dedicated Robotics or Control System Toolboxes, ensuring accessibility, reproducibility, and full transparency of the underlying models. The framework integrates several functional modules, including: (i) adaptive velocity profiling to highlight behavioral differences between AMR and AGV motion characteristics; (ii) trajectory tracking using classical Proportional–Integral–Derivative (PID) control and Model Predictive Control (MPC); (iii) obstacle avoidance based on artificial potential fields; (iv) a simplified SLAM-inspired occupancy grid mapping approach; and (v) a basic demonstration of multi-robot interaction and coordination. While no novel control or navigation algorithms are introduced, the framework enables a consistent and parametric comparison of classical and predictive control strategies within a unified simulation environment. Simulation results indicate that MPC-based control provides improved trajectory tracking accuracy and smoother motion, with reduced oscillatory behavior when compared to PID control, particularly under dynamic constraints. The obstacle avoidance and mapping modules support safe navigation in partially known environments, while the multi-robot demonstration illustrates scalable interaction principles applicable to fleet-level studies. Overall, the proposed framework constitutes a scalable and computationally efficient foundation for early-stage AMR/AGV research, benchmarking, and education, and provides a structured basis for future extensions involving advanced perception, coordination, and optimization strategies.

1.15. Comparative Analysis of Adam- and PSO-Optimized ANFIS Models for Intelligent Control of Wastewater Treatment Processes

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The effective control of industrial wastewater treatment processes based on ion-exchange resins is challenging due to their nonlinear dynamics, time-varying operating conditions, and uncertainty in water quality parameters. In particular, variations in water hardness and total dissolved solids (TDS) strongly influence purification efficiency, necessitating adaptive and intelligent control strategies beyond conventional approaches. In this study, an adaptive neuro-fuzzy inference system (ANFIS)-based intelligent control model is developed to regulate the opening degree of a control valve governing the wastewater flow rate in an ion-exchange treatment process. A laboratory-scale experimental setup was designed and implemented, and a dataset of 300 experimental samples was collected under diverse operating conditions. Water hardness and TDS were selected as input variables, while the valve opening degree was defined as the output control variable. A clustering-based rule extraction method was employed to construct the ANFIS structure, and model parameters were optimized using the Adam optimizer and Particle Swarm Optimization (PSO). The performance of the ANFIS–Adam and ANFIS–PSO models was evaluated using regression and control performance metrics, including RMSE, MAE, R^2, settling time, and integral absolute error (IAE). The results indicate that both optimization algorithms significantly enhance ANFIS performance while exhibiting complementary strengths. The ANFIS–Adam model achieves faster convergence and improved dynamic response, reducing settling time by approximately 15–20%, making it suitable for real-time control applications. In contrast, the ANFIS–PSO model demonstrates superior robustness and global search capability, achieving up to 10–15% lower RMSE and improved steady-state accuracy. Both models attain high prediction accuracy ($R^2 > 0.96$), suggesting that the choice of optimizer should be guided by specific control objectives, such as real-time responsiveness or robust offline tuning.

1.16. Comparative Evaluation of Lightweight Neural Models for Embedded Automation and Control Using Temperature and Humidity Times–Series on ESP32

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Embedded automation and control systems increasingly depend on continuous monitoring of environmental variables, particularly temperature and relative humidity, under strict energy and computational constraints. Recent advances in Tiny Machine Learning (TinyML) enable predictive models to be executed directly on microcontrollers, requiring explicit trade-offs between predictive accuracy, memory footprint, execution latency, energy consumption, and operational robustness. This work presents a comparative evaluation of three lightweight neural network architectures—a multilayer perceptron (MLP), a one-dimensional convolutional neural network (Conv1D Tiny), and a long short-term memory network (LSTM)—implemented on an ESP32 microcontroller for temperature and humidity time-series modeling. Two execution scenarios are investigated, in which both replay and field modes employ the same on-device rolling window composed of 24 valid samples. In replay mode, deterministic input data are used as a deterministic test bench for controlled validation. In field mode, the rolling window advances as new sensor samples are acquired during real operation. Experiments were conducted using an offline evaluation workflow, referred to as LiteML-Edge, employed as an experimental tool for model training, testing, and consistency checks between offline evaluation and on-device execution. Model performance is assessed using energy-aware deployment-orientated criteria central to control systems, including inference latency, flash and RAM utilization, and energy-related measurements, together with standard regression metrics such as mean absolute error (MAE), root mean squared error (RMSE), and coefficient of determination (R^2). Results indicate that the LSTM achieves higher predictive accuracy under controlled replay conditions, while the MLP demonstrates higher robustness and lower computational overhead during field operation. The Conv1D Tiny model exhibits intermediate behavior, balancing limited temporal modeling capability with moderate memory usage and energy efficiency. These results confirm that no single architecture is universally optimal and that model selection should be guided by execution context and control constraints.

1.17. Data-Driven Predictive Control of a Nonlinear CSTR Process

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Continuous stirred tank reactors (CSTRs) are challenging to control because of their nonlinear dynamics and the strong interaction between concentration and temperature. These challenges become more pronounced when operating conditions vary and reaction kinetics are uncertain, which often limits the effectiveness of conventional control strategies. In this study, a data-driven predictive control approach is developed for a generic nonlinear CSTR by integrating a Long Short-Term Memory (LSTM) neural network within an MPC framework. A benchmark exothermic CSTR described by coupled mass and energy balance equations with Arrhenius-type kinetics and jacket heat exchange is used as a reference process. Reactor concentration and temperature are selected as the state variables, while the coolant temperature serves as the manipulated input. The first-principles model is employed to generate operational data and to evaluate closed-loop performance. Dynamic simulation data are generated over 300 min with a sampling time of 0.5 min and cover multiple operating regions. Disturbances in feed concentration ($\pm$10%) and feed temperature ($\pm$5 K), together with 1% measurement noise, are introduced to reflect realistic operating conditions. An LSTM network with two hidden layers of 32 units each is trained to perform multi-step prediction of reactor states. On unseen test data, the model achieves root-mean-square errors of approximately 0.02 kmol/m^3 for concentration and 2.0 K for temperature. The trained LSTM is embedded into an MPC scheme with a prediction horizon of 10 steps and explicit input and temperature constraints. Closed-loop simulations indicate that the proposed LSTM-based MPC improves set-point tracking and disturbance rejection compared with conventional PID control and nominal model-based MPC, while achieving reduced overshoot and faster stabilization. The results suggest that data-driven predictive control provides a practical alternative for nonlinear CSTR systems when accurate mechanistic models are difficult to obtain.

1.18. Deep Learning and Embedded Systems for Vehicular Traffic Data Analysis: A Review

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The rapid development of intelligent transportation systems and connected vehicles has led to the generation of massive volumes of diverse and heterogeneous traffic data. Efficient analysis, interpretation, and classification of this data are crucial for enhancing mobility, traffic prediction, and safety in modern transportation networks. Recent studies have demonstrated that deep learning models are capable of effectively capturing both spatial and temporal dependencies in traffic datasets, enabling more accurate and reliable analysis and classification compared to traditional methods. However, most existing approaches focus solely on software-based implementations, often overlooking the practical challenges of deploying these models in real-time, resource-constrained embedded environments.

This review provides a comprehensive analysis of deep learning approaches applied to vehicular traffic data classification. It emphasizes the evaluation of model effectiveness, computational efficiency, and suitability for implementation in embedded systems, highlighting various optimization and adaptation strategies that make deployment feasible in hardware-constrained contexts.

The study also highlights current research trends, identifies critical open challenges in achieving real-time inference on limited-resource hardware, and discusses potential future directions for integrating deep learning methods with embedded systems. By bridging the gap between deep learning model design and practical hardware implementation, this review contributes to the development of intelligent, efficient, and deployable AI solutions for next-generation connected and autonomous vehicles, ultimately supporting safer and more effective transportation networks.

1.19. Design and Construction of an Integrated Electrodeionization System with Automated Control for Brackish Water Treatment

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Freshwater is a limited and precious resource, and global demand for it is growing rapidly, driven by several factors such as population growth, industrialization, and urban expansion. The growing demand for fresh water is pushing for ingenious solutions, and desalination presents itself as a concrete answer to this global challenge. This research project aims to develop an accessible and sustainable water treatment system based on the desalination of brackish water, slightly salty water that cannot be directly used for irrigation. A prototype electrodialysis (ED) device was first designed and built in the laboratory. This prototype was then equipped with an automated control system to allow the device to self-regulate. The study will validate the performance of the water produced and verify its quality for safe use in agriculture. The experimental activity focused on evaluating the performance of the self-built ED system, testing its ability to treat model saline solutions and measuring its efficiency through the ability to remove specific ions and the analysis of key parameters for water quality, including the concentration of dissolved salts. The innovative aspect of this work lies in its methodology, which provides a clear and reproducible design, and also explores the device's potential as an analytical tool. The idea is to use the ED unit not only to purify water but also to indirectly assess its quality. By monitoring changes in salinity during treatment, valuable information about the liquid's composition can be obtained. The final step is a feasibility analysis examining how the ED system can be integrated with agrivoltaics systems. Desalinated water could support crops in these innovative environments.

1.20. Design of a Robotic Hand Gripper for Pick-and-Place Operations

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The increasing demand for automation in the industry necessitates innovative solutions for efficient material handling. This work introduces the design of a robotic hand gripper for pick-and-place operations.

The design employed a multi-fingered design that integrates compliance with precision actuation mechanisms to enhance object manipulation capabilities. The gripper's structure utilizes lightweight yet durable materials, optimizing performance while minimizing energy consumption. The methodology includes computer aided design modeling and simulation to analyze the gripper's mechanics, followed by the fabrication of a prototype using 3D printing mechanisms. Incorporated as well force sensors and adaptive control algorithms to ensure real-time feedback and adjust grip strength according to various object characteristics.

Experimental results demonstrated that the robotic gripper can successfully handle objects weighing up to 5 kg with a gripping precision of ± 2 mm. The adaptability of the gripper allows it to securely grasp items ranging from cylindrical bottles to irregularly shaped containers, showcasing its versatility in diverse operational scenarios.

In conclusion, the proposed robotic hand gripper significantly enhances the efficiency and reliability of pick-and-place tasks in automated workflows. Future work will focus on refining the control algorithms and expanding the gripper's capabilities to include more complex tasks, paving the way for its application in a wide range of industrial contexts.

1.21. Enablers of Intelligent Mining Systems: Evidence from South Africa's Hard Rock Mining Industry

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The mining sector is undergoing a profound digital transformation driven by the integration of intelligent mining systems that enhance operational efficiency, safety, productivity, and ultimately sustainability. Despite the growing global adoption of smart mining technologies, their uptake within South Africa's hard rock mining industry remains uneven and underexplored. This study investigates the underlying factors enabling the adoption of intelligent mining systems in South Africa's hard rock mining industry using exploratory factor analysis. Employing a quantitative research design, data were collected through a structured questionnaire administered to actively practising mining professionals in South Africa. An exploratory factor analysis was employed to uncover the latent structures underlying the observed adoption variables. The findings reveal three distinct, statistically robust enabler clusters that collectively shape intelligent mining adoption. These include continuous awareness and knowledge development, enabling regulatory framework and public acceptance, and governmental incentive and support. The extracted factor structure demonstrates strong internal consistency and explanatory power, providing empirical evidence of the multifaceted nature of intelligent mining adoption in a developing nation context. This study contributes to the smart mining and Industry 4.0 body of knowledge by shifting the focus from barriers to actionable enablers, offering a nuanced understanding of the conditions necessary for successful digital transformation in the hard rock mining space. The results provide valuable insights for mining firms, policymakers, and technology providers seeking to accelerate the deployment of intelligent mining systems in South Africa and comparable global mining jurisdictions.

1.22. Evaluating Novel Intelligent Control Strategies for Biogas Production Using Multi-Criteria Decision Analysis

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The control of biogas production in anaerobic digestion systems is inherently challenging due to pronounced nonlinear dynamics, biological uncertainty, long time delays, and limited availability of reliable online measurements. In response, a range of advanced control strategies—including model-based, data-driven, and artificial intelligence-assisted approaches—have been proposed to enhance methane productivity while maintaining process stability. Nevertheless, a systematic and quantitatively grounded comparison of these strategies from an application-oriented perspective remains limited. This study presents a comparative assessment of novel biogas control strategies using a Multi-Criteria Decision Analysis (MCDA) framework. The evaluated alternatives include fuzzy supervisory control, adaptive neuro-fuzzy inference systems (ANFIS), mechanistic model predictive control (MPC), data-driven MPC employing machine-learning predictors, reinforcement learning-based control, and hybrid architectures that integrate soft sensors with intelligent supervisory layers. Eight evaluation criteria were defined to reflect the requirements of full-scale anaerobic digestion systems, including stability and risk prevention, methane productivity, constraint handling capability, robustness to feedstock variability, sensor practicality, implementability in PLC/SCADA environments, explainability, and lifecycle effort. The MCDA results indicate that hybrid strategies combining soft sensing with supervisory control achieved the highest aggregated performance score (0.82 on a normalized scale), followed by fuzzy (0.76) and ANFIS-based (0.74) supervisory controllers. MPC-based strategies exhibited superior constraint handling performance (criterion scores above 0.85) but were comparatively penalized due to higher modeling and implementation effort. The reported literature suggests that data-driven predictive control can improve methane yield by approximately 5–10%, while intelligent supervisory control supported by soft sensors may reduce acidification risk indicators by 20–30% relative to baseline operation. Reinforcement learning approaches demonstrated high theoretical optimization potential but the lowest industrial readiness. Overall, the proposed MCDA framework highlights hybrid intelligent control architectures as the most balanced solution, offering a practical compromise between performance enhancement, robustness, and deployability in biogas production systems.

1.23. Improved Efficiency of an Advanced Incremental Conductance Method for an Off-Grid Photovoltaic System Under Partial Shading Conditions

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The partial shading phenomenon is one of the most critical issues in off-grid photovoltaic systems that may decrease their performance. Therefore, the utilization of efficient and robust maximum power point tracking (MPPT) methods is crucial in these systems, especially under highly abrupt variations. In the domain, several researchers developed classic control techniques such as Incremental Conductance (IC) algorithms that often exhibit high fluctuations and slow convergence during challenging scenarios. This work presents an advanced Incremental Conductance (AIC) MPPT control technique specifically suggested to enhance the tracking efficiency and performance under Partial Shading Conditions (PSCs). The suggested method presents a modified step size that adaptively adjusts the control action according to operating conditions, allowing fast convergence with negligible oscillations. This technique is applied in off-grid mode, which consists of a PV array and a DC-DC step-up converter linked to a resistive DC load, using MATLAB/Simulink software, version 2020b. Simulation results are performed under complex PSC test, confirming the robustness and resilience of the proposed control strategy that rapidly attains the maximum power point (MPP) in less than 0.2 s and significantly enhances tracking efficiency and reduces steady-state fluctuations compared to the benchmarked traditional IC method, thereby contributing to optimized reliability in off-grid PV systems.

1.24. Intelligent Modeling and Optimization of Gas Consumption in Steam-Based Tire Vulcanization Using ANFIS

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The increasing demand for energy-efficient and high-quality tire manufacturing requires advanced control strategies capable of handling the nonlinear and time-varying characteristics of the vulcanization process. Conventional control methods often struggle to maintain optimal operating conditions and minimize energy consumption under varying technological and material parameters, which has led to growing interest in intelligent data-driven control approaches. In this study, an adaptive neuro-fuzzy inference system (ANFIS)–based model is developed for intelligent modeling and optimization of the tire vulcanization process in a steam-heated vulcanization press. Four key process variables, vulcanization temperature, steam pressure, tire mass, and process time, are selected as input parameters, while the gas consumption rate is considered as the output control variable. These variables are chosen based on the physical characteristics of the process and practical operating conditions in light-vehicle tire production. A dataset consisting of 250 experimentally consistent process samples is used to train and validate the ANFIS model using the Python programming environment. The model is optimized using Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Gradient Boosting-based tuning strategies. Model performance is evaluated using root mean square error (RMSE), mean absolute error (MAE), and coefficient of determination (R^2). The results demonstrate that the optimized ANFIS model effectively captures the nonlinear relationship between the process parameters and gas consumption. The best-performing configuration achieves a high predictive accuracy with $R^2 \approx 0.945$, while maintaining low prediction errors (RMSE = 0.018–0.025 m^3/min, MAE = 0.012–0.017 m^3/min). These findings confirm the effectiveness of the proposed approach and its potential for intelligent and energy-efficient control of tire vulcanization processes.

https://doi.org/10.3390/engproc2026145006

1.25. Intelligent Security Hardening of SCADA Systems Using Machine Learning Algorithms

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Supervisory Control and Data Acquisition (SCADA) systems play a key role in various industrial processes. Due to their key role in critical infrastructures, in recent years, they have become the target of cyber attackers. Although some security hardening solutions have been proposed to secure them, traditional security measures such as firewalls, intrusion detection systems, and access controls are not enough to provide adequate protection against modern cyber threats. Therefore, there is a need for novel security hardening solutions that can detect and respond to emerging, previously unknown threats. In parallel with this, in this research, we propose an intelligent security hardening approach for SCADA systems using machine learning algorithms. The proposed approach relies on the collection and analysis of network traffic data from SCADA systems, followed by the application of machine learning algorithms to detect and respond to cyber threats. Network traffic data collected from various sources are analyzed to identify anomalies that may indicate the presence of cyber threats. Various machine learning algorithms are used to analyze the data. The proposed approach can improve the security of SCADA systems and reduce the risk of downtime and financial losses due to cyber attacks. It is a more cost-effective security solution compared to traditional security measures.

1.26. Justification of Design Parameters and Control System for Manipulator-Actuated Fire Monitors in Robotic Firefighting Systems

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Introduction. Robotic firefighting systems equipped with manipulator-actuated fire monitors (water/foam nozzles) enable remote suppression in hazardous environments while reducing personnel exposure. However, accurate jet aiming and stable operation are challenged by strong, rapidly varying disturbance loads caused by jet recoil, flow-rate changes, hose/line dynamics, and platform motion. These factors must be explicitly considered when justifying manipulator design parameters and selecting a control architecture that maintains pointing accuracy and operational safety.

Methods. A coupled dynamic model of the manipulator–fire–monitor assembly was formulated, incorporating joint friction, actuator limits, and a recoil load model expressed through nozzle operating variables (pressure/flow) and monitor orientation. Design parameter justification was performed by evaluating worst-case combinations of required slewing/positioning maneuvers and recoil disturbances to derive bounds for joint torques, speeds, transmission ratios, stiffness, and admissible mass-inertia properties of the end-effector. The control system was synthesized as a two-layer scheme: a feedforward compensation term based on the estimated recoil moment and desired motion profile, and a feedback loop for tracking and disturbance rejection (computed-torque or robust PID structure with anti-windup and saturation handling). Safety constraints were enforced through bounded acceleration/jerk commands and workspace limitations.

Results. The proposed framework yields parameter maps linking nozzle operating regimes and aiming dynamics to required actuator capabilities and structural margins.

Simulation-based verification demonstrates stable tracking under abrupt flow changes and external disturbances, with reduced overshoot and faster settling compared to non-compensated control. The controller maintains bounded pointing error while avoiding actuator saturation across the considered operating envelope.

Conclusions. The presented approach provides a systematic justification of manipulator design parameters and control structure for manipulator-actuated fire monitors. It supports evidence-based sizing and tuning to improve aiming stability, robustness to recoil disturbances, and overall safety of robotic firefighting systems.

1.27. Mechanical Design Based on the Pelican Optimization Algorithm

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Introduction: The Pelican Optimization Algorithm (POA) is a meta-heuristic optimization algorithm, distinguished by its excellent ability to balance global exploration and local exploitation. This unique advantage enables it to effectively tackle complex multi-objective and multi-constraint optimization problems in mechanical design, where traditional algorithms often struggle with precision and efficiency. Thus, exploring POA's application value in this field is of great significance for advancing mechanical design optimization.

Methods: This study applies the POA to mechanical design parameter optimization, taking advantage of its bionic mechanism that simulates pelicans' natural hunting behavior. To verify its performance, POA is employed to solve three mechanical design optimization tasks: minimizing the self-weight of tension/compression springs, reducing the volume of rolling bearings, and lowering the manufacturing cost of reducers, with parameter optimization conducted by leveraging POA's balanced exploration–exploitation capability.

Results: Comparative experimental tests show that the mechanical design solutions obtained by POA outperform those generated by other conventional meta-heuristic algorithms. Specifically, in terms of core objective function values, including the self-weight of springs, volume of rolling bearings, and production cost of reducers, POA achieves more optimal results, demonstrating its superior optimization performance.

Conclusions: The application of POA effectively enhances the precision and efficiency of mechanical design parameter optimization. This study confirms the feasibility, superiority, and practical applicability of POA in solving engineering optimization problems, providing a reliable new optimization tool for related mechanical design scenarios.

1.28. Multi-Objective Optimization of Methanol–Diesel RCCI Combustion for Sustainable Engine Performance

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This work evaluates how varying the methanol energy share affects efficiency, combustion behavior, and pollutant formation in a methanol–diesel-fueled Reactivity-Controlled Compression Ignition (RCCI) engine. A comprehensive experimental campaign was performed under both constant and dynamically varying operating conditions, covering engine speeds from 1400 to 2000 rpm and load levels ranging between 25% and full load. The methanol substitution rate (MSR) was systematically adjusted from 0% to 40% to assess its influence on combustion and emission performance. The findings demonstrate that a higher methanol contribution significantly improves brake thermal efficiency, with gains reaching approximately 14% at elevated load conditions. However, excessive methanol addition slightly increases cycle-to-cycle variations, indicating a modest reduction in combustion stability. Changes in MSR were also observed to strongly influence gaseous and particulate emissions. Compared with conventional diesel operation, increasing methanol fraction led to notable reductions in nitrogen oxides and particulate matter, while carbon monoxide levels exhibited sensitivity to combustion phasing and mixture reactivity. Analysis of the measured data revealed that NOx emissions declined by nearly 30–50% at higher methanol fractions, and particulate emissions remained considerably lower than those produced by diesel-only combustion. In addition, vibration-based virtual sensing combined with time–frequency domain analysis showed that methanol enrichment modifies heat release characteristics and pressure rise rates, which subsequently alters engine structural vibration responses and emission trends. Exergy assessment further indicated that a methanol substitution ratio of approximately 30% minimizes irreversibility losses, signifying superior energy utilization efficiency and the most thermodynamically favorable combustion condition within the tested range.

1.29. Neural Architecture Search-Driven Multi-Objective Coordinated Load Frequency Control and Automatic Voltage Regulation for Renewable-Dominated Multi-Area Power Systems

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The large-scale integration of renewable energy sources (RESs), electric vehicles (EVs), and battery energy storage systems (BESSs) has significantly reduced system inertia and intensified frequency–voltage coupling in modern interconnected power systems, thereby challenging the effectiveness of conventional secondary control strategies. To address these emerging issues, this paper proposes an intelligent, control-aware evolutionary multi-objective Neural Architecture Search (EMO–NAS) framework for coordinated Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR) in renewable-dominated multi-area power systems. Unlike existing approaches that rely on fixed or heuristically selected controller structures, the proposed framework treats the controller architecture itself as an explicit decision variable and autonomously synthesizes task-specific control policies through multi-objective evolutionary optimization. The coordinated LFC–AVR problem is formulated by simultaneously minimizing frequency deviation, tie-line power oscillations, voltage deviation, rate of change of frequency (RoCoF), control effort, and robustness degradation, while satisfying practical operational constraints including generation rate limits, actuator bounds, and BESS state-of-charge restrictions. A structured NAS search space incorporating feedforward, recurrent, and temporal architectures is evaluated using closed-loop time-domain simulations under realistic disturbances, renewable intermittency, EV variability, and parameter uncertainty. Feasibility and stability are enforced through constraint-aware penalties and robust domain randomization. Comprehensive simulation studies on three- and four-area interconnected systems demonstrate that the proposed EMO–NAS controller achieves substantial performance improvements compared with optimally tuned fractional-order PID, robust sliding mode, and fixed-architecture neural controllers. Quantitatively, reductions of approximately 30–35% in frequency deviation, 25–35% in tie-line power oscillations, and up to 30% in RoCoF are achieved, while completely eliminating constraint violations. Robustness analysis under $\pm 50\%$ parameter uncertainty and Monte Carlo simulations further confirm superior stability, generalization, and scalability. These results establish architecture-level optimization as a powerful and systematic pathway for designing robust, coordinated secondary controllers in future low-inertia, renewable-dominated power systems.

1.30. Real-Time Validation of a Robust Intelligent Control Technique for Grid-Tied Photovoltaic Systems

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The global demand for clean, renewable energy sources has significantly increased, particularly for photovoltaic (PV) systems, which require less maintenance and operational costs. They are known for their flexibility to support both off-grid and grid-connected applications, making them a key technology for modern sustainable energy systems. Grid-Tied PV Systems (GTPVSs) have attained attention due to their capability of injecting power directly into the electrical grid without the need for batteries, unlike the grid-off PV systems that require energy storage. The use of GTPVS minimizes battery maintenance and ensures the direct synchronization of the extracted PV power with the utility grid. Nevertheless, abrupt variations and partial shading in environmental conditions and grid disturbances may reduce the robustness and efficiency of these systems. For this purpose, improved and advanced control techniques are required for establishing high performance and superior power quality injection. The utility of these methods is crucial for establishing a fast tracking of the Maximum Power Point (MPP) and enabling a stable grid injection with international standard compatibility. Thus, a Robust Intelligent-Fuzzy Backstepping (RI-FB) control technique is introduced for improving the performance of GTPVS, by providing a fast tracking under Partial Shading Conditions (PSCs) and delivering a rapid power injection into the grid, even under grid disturbances, such as AC loads. The integration of robust backstepping and fuzzy logic ensures an optimal power tracking that exceeds 98% in only 18 ms while maintaining the grid synchronization, and offering a minimized Total Harmonic Distortion (THD) below 0.90%, surpassing other benchmarked strategies. The proposed RI-FB technique confirms its real-time feasibility through Processor-In-the-Loop (PIL) implementation using the TMS320F28335 platform, which presents a robust key for the GTPVS.

1.31. Reinforcement-Learning-Guided Particle Swarm Optimization for Robust Quadcopter PID Controller Tuning

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Introduction: Cascaded PID control remains popular in quadcopter platforms because it is simple to implement and certify; however, tuning the coupled attitude–altitude loops is often time-consuming and sensitive to disturbances, actuator limits, and model mismatch. This work targets the inner-loop controller of an existing MATLAB/Simulink quadcopter model, where four PIDs regulate roll (φ), pitch (θ), yaw (ψ), and altitude (z) under an outer-loop command generator.

Methods: Three tuning strategies are compared under an equal simulation budget: (i) a classical baseline using Simulink PID Tuner followed by manual refinement, (ii) particle swarm optimization (PSO) directly optimizing the 12 PID gains, and (iii) reinforcement-learning-guided PSO (RL-PSO), where PSO searches the gain vector while an RL agent adapts PSO hyperparameters (inertia weight and acceleration coefficients) online based on swarm progress and diversity features. The objective function combines integrated time-weighted absolute error (ITAE) tracking terms for φ, θ, ψ, and z with penalties on overshoot, control effort, actuator saturation, and unstable responses.

Results: A robustness benchmark is defined using two disturbance-focused scenarios: (1) feedback-path perturbations and (2) plant-side disturbances. Performance will be reported using Monte-Carlo statistics of RMS error, overshoot, settling time, control effort, and constraint violations, together with convergence curves (best cost versus iteration and total model evaluations). The study is designed to test the hypothesis that RL-PSO improves worst-case disturbance rejection and reduces constraint violations relative to standard PSO and classical tuning.

Conclusions: RL-PSO provides a practical, simulation-based route to robust multi-loop PID tuning for quadcopter attitude–altitude control without altering the overall cascaded control structure.

1.32. Singular Frequencies Based Robust PID Controller Design and Analysis in Parameter Space

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Finding the complete set of stabilizing parameters for a Proportional–Integral–Derivative (PID) controller is a long-standing challenge in control engineering, especially when dealing with high-order systems. This study proposes a practical computational framework to map the entire stability region in the (Kp, Ki, Kd) parameter space utilizing the singular frequency decoupling method. By fixing the proportional gain (Kp), the boundaries of the stability region in the (Ki, Kd) plane are analytically derived using linear equations. This approach allows for the automatic identification of stabilizing polygons without the need for complex and time-consuming grid-based searches. A key focus of this work is the extension of this methodology to handle parametric uncertainties within interval plants. Instead of relying solely on traditional methods, this study employs a robust analysis based on vertex plant configurations. "By evaluating the stabilizing proportional gain intervals for the extreme corners of the uncertainty box and finding their mathematical intersection, a common solution region is identified. Furthermore, robust stability within the (Ki, Kd) plane is ensured by intersecting the stabilising polygons of the individual vertex plants and conducting a robust stability analysis of the parameter space, taking into account the uncertain plant parameters." To validate the approach, various representative system models are examined and analyzed. The results demonstrate that the proposed method provides a reliable and efficient tool for designers to determine robust controller gains with guaranteed stability, visualized through 2D robust polygons and 3D stabilizing solids.

1.33. The 3D-Printed Low-Cost 6-DoF Robot Adolfo: Technology Overview and Benchmarking

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Fully articulated 6-degree-of-freedom (6-DoF) robotic manipulators remain one of the most versatile architectures in industrial robotics due to their high dexterity and capability to perform complex spatial tasks. However, their widespread adoption is often limited by cost, system complexity, and reduced accessibility for small-scale industry, research, and education. Recent advances in Additive Manufacturing (AM), particularly low-cost 3D printing technologies, are enabling new design paradigms that challenge conventional approaches to robotic arm development by increasing geometric freedom, modularity, and manufacturing accessibility. This paper presents a comprehensive technology overview and benchmarking study of the Adolfo, a low-cost 6-DoF robotic manipulator developed by Smile.Tech, whose mechanical structure is predominantly produced using 3D-printed components. The work addresses the multidisciplinary aspects of the system, including mechanical architecture, actuation strategy, control and interface software, and compatibility with virtual operation and simulation environments. A concise review of the current state of the art in industrial and collaborative 6-DoF manipulators is provided to contextualize the proposed solution. To assess the positioning of the Adolfo within the existing market landscape, a benchmarking analysis is conducted against representative commercial robotic arms, focusing on key operational and technical indicators such as payload-to-weight ratio, workspace, repeatability, structural design, cost range, and software ecosystem. The results highlight the trade-offs between performance, cost, and manufacturability inherent to low-cost, additively manufactured robotic systems, while identifying application domains where such platforms offer a competitive and flexible alternative to conventional industrial solutions. The presented study aims to support informed decision-making in the selection and development of accessible 6-DoF robotic platforms for research, education, and light industrial applications, with particular relevance for human–robot collaboration in Industry 5.0 manufacturing contexts.

1.34. The Adaptive and Optimization-Enhanced ANFIS Control of a Solar Drying System Under Variable Operating Conditions

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Solar drying systems provide an energy-efficient and environmentally sustainable solution for processing agricultural and medicinal products; however, their performance is strongly influenced by nonlinear process dynamics, fluctuating solar irradiation, and continuously changing ambient conditions. These uncertainties often lead to unstable temperature and humidity regimes, increased energy consumption, and the degradation of product quality when conventional fixed-parameter control strategies are applied. Therefore, the development of intelligent and adaptive control approaches capable of ensuring robust operation under highly variable conditions remains an important challenge in modern automation and mechatronic systems. In this work, an advanced adaptive control framework based on an Adaptive Neuro-Fuzzy Inference System (ANFIS) is proposed for a cabinet-type solar drying system. The controller is formulated using a first-order Sugeno fuzzy inference structure with Gaussian membership functions and trained through a hybrid learning algorithm that combines least-squares estimation with gradient-based optimization. To further enhance adaptability and robustness, the ANFIS parameters are optimized using a particle swarm optimization (PSO) algorithm, while physical constraints derived from heat and mass transfer principles are explicitly incorporated into the control design. The complete control architecture is implemented in a MATLAB/Simulink environment, enabling digital-twin-based simulation and comprehensive performance evaluation. The simulation results demonstrate that the proposed optimization-enhanced adaptive ANFIS controller significantly improves temperature and humidity regulation compared to conventional control approaches. Faster setpoint tracking, reduced overshoot, and improved disturbance rejection are achieved under variable solar irradiance and ambient conditions. Quantitative analysis indicates a reduction in settling time of approximately 30% and a decrease in energy consumption by about 12–18% while maintaining stable and efficient drying regimes. The obtained results confirm that integrating adaptive neuro-fuzzy control, metaheuristic optimization, and physics-informed constraints provides an effective and scalable solution for complex nonlinear solar drying processes. The proposed framework can be extended to other renewable energy-driven thermal and mechatronic systems.

1.35. Virtual and Experimental Proof of Concept of a Delta Robot for Automated Packing of Automotive Metal Plates

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Manual handling and packing of thin metal plates remains a labor-intensive operation in the automotive manufacturing sector, frequently requiring multiple operators and resulting in limited productivity, reduced process repeatability, and ergonomic constraints. This paper presents a preliminary virtual and experimental proof of concept for the automation of such a packing task using a delta robot, motivated by a representative industrial scenario involving automotive heat exchanger plates. The proposed study adopts an intentionally simplified problem formulation to support early-stage feasibility assessment and system design. In the considered scenario, the approximate initial position of each plate is assumed to be known at the moment it is released onto a tray, allowing the study to focus on the robotic packing stage rather than on part detection. A virtual robotic packing cell is developed using MATLAB-based simulation tools, with particular emphasis on workspace definition, packing layout design, and end-effector selection. The target placement positions inside the packing tray are fully defined in the robot coordinate system, enabling the analysis of reachability, packing density, and achievable cycle times without introducing additional complexity related to sensing or perception. A set of performance-oriented indicators is defined and evaluated in simulation, including workspace utilization, throughput, and packing efficiency. Based on the virtual results, a simplified experimental demonstrator is implemented to provide initial validation of the proposed concept, using representative plate geometries and a programmed packing sequence. This experimental stage is not intended as a full industrial validation, but rather as a functional verification of the feasibility of delta robot-based packing under controlled conditions. By deliberately limiting the system scope, the study establishes a baseline for robotic packing performance and provides a structured foundation for subsequent research, which will address more realistic industrial conditions such as imprecise plate positioning, surface contamination, vision-based perception, robot–sensor calibration, and scenarios involving multiple plates simultaneously.

1.36. Vision-Based Chessboard Perception and Coordinate Mapping for Delta Robot Pick and Place

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Vision-guided robotic manipulation plays a central role in flexible and low-cost automation systems, particularly for structured pick-and-place tasks. This paper presents a proof-of-concept study focused on vision-based perception and coordinate mapping for a delta robot, using a chessboard as a structured benchmark environment. The chessboard provides a regular grid with known geometry, enabling a systematic evaluation of computer vision techniques for object localization and robot-oriented spatial mapping. The proposed framework prioritizes visual perception over advanced control, aiming to extract reliable spatial information from camera input and convert it into robot-ready coordinates. A camera-based vision pipeline is developed using OpenCV to detect the chessboard, estimate its pose through corner detection and homography, and segment individual squares of the board. Chess piece presence and position are determined through color segmentation and contour analysis, allowing square occupancy estimation and centroid extraction. Camera calibration and board-plane registration enable the transformation of image coordinates into the delta robot workspace, providing target positions for pick-and-place actions. To assess robustness and performance, classical computer vision approaches are compared with convolutional neural network-based classifiers integrated via OpenCV's DNN module for chess piece detection and classification. The methods are experimentally evaluated under varying lighting conditions in terms of detection accuracy, processing latency, and computational load. The results highlight practical trade-offs between classical and learning-based vision techniques for structured manipulation tasks, particularly regarding robustness and real-time feasibility. Although demonstrated in a chessboard scenario, the proposed approach is directly applicable to grid-based industrial operations such as kitting, tray loading, and fixture-based assembly. This work establishes a practical foundation for vision-based coordinate mapping in delta robot pick-and-place applications and supports future extensions toward more complex perception and manipulation strategies.

2. Condition Monitoring and Fault Diagnosis

2.1. An Intelligent Deep Learning Assisted ABC–NSGA-II Algorithm for Multi-Objective Directional Overcurrent Relay Coordination in Smart Grid

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The high penetration of distributed generation, inverter-interfaced renewable energy sources, and dynamic microgrid operation has drastically transformed short-circuit behavior, leading to frequent miscoordination of conventional protection schemes. Bidirectional fault currents, variable fault levels, and network reconfiguration further complicate the coordination of directional overcurrent relays (DOCRs). To overcome these challenges, this paper proposes a deep learning–enabled hybrid Artificial Bee Colony (ABC) and NSGA-II–based multi-objective optimal protection coordination (DL–ABC–NSGA-II MO-OPC) framework for renewable-integrated power systems. The protection coordination problem is formulated as a constrained multi-objective optimization model, aiming to: (i) minimize the total operating time of primary and backup relays, (ii) maximize coordination margins under coordination time interval (CTI) constraints, and (iii) enhance protection security under bidirectional inverter-dominated fault currents and multiple network topologies. The decision variables include time multiplier settings (TMSs), plug setting currents (PSCs), and relay curve characteristics. A deep learning model is embedded within the ABC search process to predict promising regions of the search space, accelerate convergence, and adaptively tune control parameters under varying fault and loading conditions. The refined solutions are then evolved using NSGA-II to generate a well-distributed Pareto-optimal front. The proposed DL–ABC–NSGA-II framework is validated on a modified benchmark power network under grid-connected and islanded modes, considering multiple fault types and renewable penetration scenarios. Simulation results confirm a substantial reduction in overall relay operating time, complete elimination of miscoordination, and strong robustness against renewable-induced fault current uncertainty. Comparative analysis with conventional coordination and recent metaheuristic-based approaches demonstrates the superior convergence speed, enhanced solution diversity, and improved protection reliability of the proposed scheme. The proposed deep learning–assisted protection coordination strategy provides a scalable, intelligent, and cyber-resilient solution for next-generation smart grids and microgrids with high renewable energy penetration.

2.2. Region-Focused CNN Framework for Reliable Visual Inspection of UV Adhesive Deposition in NVMe SSD Manufacturing

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Automated visual inspection plays a central role in electronics manufacturing processes involving UV adhesive deposition, where undetected defects may compromise mechanical stability and lead to latent failures. In NVMe solid-state drive (SSD) production, inspection systems must prioritize reliability and defect containment, as false negatives represent a critical operational risk. Despite this requirement, many deep learning-based inspection approaches remain optimized for global accuracy metrics, which are not fully aligned with industrial reliability constraints. This paper presents a convolutional neural network (CNN)-based visual inspection framework tailored for high-reliability deployment in NVMe SSD manufacturing. The proposed approach emphasizes inspection problem formulation rather than architectural complexity. A physically coherent region of interest (ROI) was defined to encompass the functional UV adhesive deposition area surrounding the SSD controller, reducing background interference. Three CNN backbones—ResNet50, EfficientNetV2, and MobileNetV2—were evaluated under identical conditions using transfer learning. Additionally, multiple decision strategies, including calibrated decision thresholds, were analyzed to reduce false negatives while controlling false-positive rates. All experiments were conducted using an industrial dataset collected from an operational production line. Experimental results indicate that ResNet50 achieved stable accuracy at around 86% but showed limited reliability due to elevated false-positive rates. In contrast, EfficientNetV2 and MobileNetV2 achieved a defective part recall above 98%, overall accuracy exceeding 91%, and a reduction of more than 50% in false negatives compared to the ResNet50 baseline. MobileNetV2 matched the performance of EfficientNetV2 while maintaining lower computational complexity. The results demonstrate that reliability gains in industrial visual inspection are more effectively achieved through region-focused analysis and decision-level optimization than by increasing model complexity. The proposed framework is suitable for deployment in high-throughput manufacturing environments and provides a basis for future extensions involving hybrid inspection strategies.

2.3. Comparative Study on Modeling of Temperature Field During Peripheral Grinding of Steel Parts Using Machine Learning Methods

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The grinding process is a common choice for finishing of mechanical parts in industrial practice where both surface quality and integrity are required to be maintained at sufficiently high levels. As it is not always possible to obtain all the necessary information for process monitoring through experimental measurements, it is often necessary to develop numerical models, which can be validated based on experimental data and then used to predict various outcomes of the grinding process such as the temperature or the stress field in the workpiece. Nevertheless, when specific responses are required to be predicted in real time, numerical models cannot be directly used due to their computational cost and thus, machine learning methods can be employed as an alternative choice. In order to determine a method which can achieve both the required level of accuracy and reduced computational cost, two different models, namely NARX (nonlinear autoregressive exogenous model) and LSTM (long-short term memory), are compared for a case of peripheral grinding of steel components under different process conditions. Both machine learning models are trained based on data from a validated numerical model, and their accuracy regarding the prediction of temperature field in every case is evaluated through various criteria.

2.4. Condition Monitoring of Rolling Bearings in PMSM Drives Under Variable Operating Conditions

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A comprehensive approach to diagnosing rolling bearing damage in permanent magnet synchronous motors (PMSMs) is an important research topic due to the growing use of PMSM drives in industrial systems. The proposed methodology is based on the analysis of diagnostic signals, including mechanical and electrical quantities, obtained under varying operating conditions. Experimental studies were conducted for different motor load levels, as well as for different settings of the current controller parameters in a field-oriented control system. This made it possible to assess the impact of operating conditions and control structure on the effectiveness of bearing damage detection. Particular attention was paid to the process of signal acquisition, preprocessing, and extraction of features characteristic of rolling bearing damage. The selected methods of time and frequency domain signal analysis were used to identify damage-sensitive symptoms associated with bearing component defects. The results obtained show that the effectiveness and sensitivity of individual diagnostic symptoms strongly depend on both the type of signal measured and the operating conditions of the drive system. A comparative evaluation of the extracted features is presented, emphasizing their usefulness for reliable damage detection and accurate condition assessment. The presented approach shows potential for the practical application of signals other than mechanical vibrations.

2.5. Current-Based Induction Motor Eccentricity Classification with a Compact CNN Trained on Residual-Augmented Simulation Data

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Accurate induction motor eccentricity detection from phase currents is attractive for industrial monitoring because it can be implemented non-invasively using existing electrical measurements. However, developing robust neural classifiers is often limited by the scarcity of labeled fault data across operating conditions. This work proposes a compact convolutional neural network (CNN) for eccentricity-level classification, trained on a broad set of simulated current signals enhanced to better reflect measurement imperfections, and designed as a foundation for future transfer to real-machine recordings.

Three-phase stator currents were generated with an eccentricity simulation model and enriched using a residual-injection scheme motivated by frequency-domain inspection and correlation analysis, which indicate notable non-ideal components affecting signal consistency. The dataset spans five eccentricity levels (0.0–0.4, step 0.1), steady loads from 0 to 10 (step 2), and 1 Hz sinusoidal load profiles within 0–4, 4–6, and 6–10, for steady speeds of 1500, 1350, and 1200 rpm. From each case, 50 windows of 900 samples were extracted and reshaped into a $30 \times 30 \times 3$ representation (three channels for phase currents). The CNN includes three convolutional feature-extraction blocks (convolution, batch normalization, ReLU, max pooling) and a classifier head with adaptive average pooling, dropout, and a fully connected layer.

The proposed network achieved approximately 96% test accuracy, with comparable validation accuracy and ~97% training accuracy across the considered conditions.

A lightweight CNN can accurately classify eccentricity levels using current-only inputs when trained on condition-diverse, residual-augmented simulation data. In future work, the trained model will serve as a pretraining baseline for transfer learning to laboratory measurements, enabling practical eccentricity detection on real motors.

2.6. Design and Implementation of an SDM630-Based Energy Monitoring System for Three-Phase Electrical Machine Applications

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This paper presents the design and implementation of an energy monitoring system based on the SDM630 multifunction meter, developed for applications involving three-phase electrical machines. The main objective of the proposed system is to provide a practical solution for monitoring and analyzing the operating behavior of electrical machines in both industrial and laboratory settings. The system performs real-time measurement and continuous logging of key electrical parameters, including phase and line voltages, currents, active and reactive power, energy consumption, power factor, and frequency. Data communication between the SDM630 m and the unit of monitoring is implemented using the Modbus RTU protocol, selected for its suitability and reliability for industrial environments. Measured data are stored locally and processed offline to enable further analysis. Statistical processing is applied to assess operating conditions, identify energy consumption trends, and evaluate the stability of machine performance under different loading conditions. Parameters such as mean values, fluctuations, and temporal trends are considered to support energy evaluation and basic diagnostic analysis. The system architecture was designed with flexibility in mind, allowing straightforward integration with supervisory systems and potential future extensions, including remote monitoring and data visualization platforms. Experimental tests were conducted on three-phase electrical machines operating under various load conditions levels. The experimental results demonstrate that the proposed system provides consistent and accurate measurements, confirming its suitability for continuous monitoring tasks. Owing to its straightforward design, low implementation cost, and reliance on commercially available components, the developed system offers an effective and accessible solution for energy management, performance assessment, and power quality monitoring in three-phase electrical machine applications.

2.7. Digital Transformation with Asset Administration Shell Methodology Proposal

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Industry 4.0 drives the evolution toward efficient, intelligent, and interconnected production systems, where standardized digital twins—centered on the Asset Administration Shell (AAS)—provide a unified digital representation of physical and logical assets.

This paper demonstrates a comprehensive digitalization methodology by transforming a legacy industrial electric screwdriver into a fully compliant Industry 4.0 component, serving as a concrete case study. The approach rigorously follows the RAMI 4.0 reference architectural model and the Acatech Industry 4.0 Maturity Index principles, enabling progressive maturity advancement in brownfield environments.

The generic, replicable process consists of six modular stages adaptable to virtually any industrial asset: (i) asset characterization, functional analysis, and digitalization objective definition; (ii) creation of a Type 1 AAS (static/digital master) using standardized submodel templates for semantic description; (iii) design and deployment of low-cost/custom IoT sensing hardware to capture relevant real-time data (e.g., energy, usage, condition); (iv) bidirectional integration linking the physical asset to its digital representation; (v) implementation of a dynamic Type 2 AAS with secure runtime interfaces (e.g., OPC UA server); and (vi) real-time data access, visualization, and analytics via standardized clients.

This standardized, scalable methodology offers a practical blueprint for retrofitting legacy equipment without requiring full system replacement, thereby accelerating Industry 4.0 adoption across diverse manufacturing domains. The screwdriver implementation validates how standardized digital twins enable enhanced condition monitoring, energy transparency, predictive insights, data-driven decision-making, and improved operational efficiency and sustainability.

2.8. Digital Twin–Enabled Condition Monitoring and Predictive Fault Diagnosis of Critical Assets

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https://doi.org/10.3390/engproc2026145006

Critical assets such as power generation equipment, industrial machinery, transportation infrastructure, and manufacturing systems are essential to the reliability and safety of modern socio-technical environments. Unexpected failures in these assets can result in costly downtime, safety risks, and service disruptions. Conventional condition monitoring and fault diagnosis approaches—often based on periodic inspections, fixed thresholds, or isolated data analysis—are increasingly inadequate for complex assets operating under variable and uncertain conditions. In this context, Digital Twin-enabled condition monitoring and predictive fault diagnosis offers a powerful, data-driven paradigm for proactive asset health management.

This study proposes a Digital Twin-based framework that integrates real-time sensor data, physical system models, and advanced analytics to enable continuous monitoring and predictive fault diagnosis of critical assets. The Digital Twin acts as a dynamic virtual replica of the physical asset, continuously updated through operational data streams such as vibration, temperature, electrical, and process signals. Machine learning and statistical inference techniques are employed to detect anomalies, identify fault signatures, and capture degradation trends, while physics-informed constraints ensure consistency with underlying system behaviour. A key feature of the proposed approach is its predictive capability. By embedding remaining useful life estimation and fault progression modelling within the Digital Twin, the framework enables early warning of impending failures and supports proactive maintenance planning. Asset operators can evaluate "what-if" scenarios, assess the impact of operating conditions on asset health, and optimise maintenance strategies to minimise downtime and lifecycle costs. The effectiveness of the framework is demonstrated through illustrative use cases involving representative critical assets, showing improved fault detection accuracy and earlier diagnosis compared to conventional monitoring methods. Overall, this work highlights Digital Twin–enabled condition monitoring as a foundation for intelligent, predictive asset management, supporting enhanced reliability, safety, and operational efficiency in critical infrastructure and industrial systems.

2.9. Digital Twins for Condition Monitoring in Offshore Facilities: Opportunities and Gaps

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Harsh and extreme marine and environmental conditions have a great impact on offshore energy systems, oil and gas platforms, and wind farms. Extreme waves, corrosion from seawater/microorganisms, and the remote nature of these facilities demand continuous monitoring to prevent costly total shutdowns or accidents caused by corrosion and wave-induced vibrations. Condition monitoring of offshore facilities involves using multi-source data fusion from sensors to enable real-time data analytics, coupled with AI models to obtain facility insights. Digital twin provides integrated real-time analysis, alarms, and an AI-based approach that represents a paradigm shift in condition monitoring for offshore facilities by offering a virtual replica that can simulate real-time degradation.

We reviewed traditional methods and compared them to recent advances that fused physics-based models and AI into a digital twin. We review technologies such as blockchain, CNN-based algorithms, physics-augmented AI, physics-informed neural networks (PINNs), graph neural networks (GNNs), federated learning, and their suitability in creating offshore facilities digital twins. We investigated digital twin architectures, implementation and integration strategies, challenges, and provided a forward-looking roadmap.

Our review reveals that traditional approaches often struggle with multi-fault complexity and data corruption from harsh environments, leading to higher false positives/negatives in fault detection and limited predictive accuracy. In contrast, digital twins integrating physics-informed models achieve superior predictive performance, due to their robust handling of noisy/multi-source data. The digital twins approach reported lower root-mean-square errors and better generalisation in corrosion-fatigue and structural fatigue scenarios, leading to improved forecasting accuracy for unplanned downtime, maintenance costs, and the useful lives of facilities and equipment. Our review also highlighted a research-to-practice gap in the scalability of the proposed solution, data privacy, and cross-operator data-sharing capabilities.

2.10. Driving Operational Performance Through Predictive Maintenance: Evidence from Industrial Condition Monitoring and Fault Diagnosis Data

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Predictive maintenance enabled by condition monitoring and fault diagnosis (CMFD) has emerged as a critical operational capability for improving equipment reliability and production continuity. However, empirical evidence based on real operational data linking CMFD to performance outcomes remains limited within the operations and supply chain management literature. This study examines how condition monitoring intensity and fault diagnosis effectiveness influence maintenance efficiency, unplanned downtime, and operational performance using secondary industrial datasets from manufacturing environments. Drawing on maintenance strategy and operations performance theory, a causal framework is developed connecting CMFD capabilities to productivity, cost efficiency, and service reliability through maintenance effectiveness. The analysis employs panel regression and mediation techniques to evaluate performance changes associated with predictive maintenance interventions across multiple equipment units and time periods. The findings demonstrate that enhanced monitoring frequency and improved fault detection accuracy significantly reduce unplanned downtime and maintenance costs while increasing throughput and delivery reliability. Maintenance effectiveness is shown to mediate the relationship between CMFD capabilities and operational performance outcomes. This research contributes to operations and supply chain management literature by empirically establishing predictive maintenance as a strategic operational capability rather than solely a technical tool. Managerially, the results provide evidence-based justification for investments in CMFD technologies as drivers of operational efficiency, resilience, and sustainable performance.

2.11. Experimental Comparison of Low-Cost Piezoelectric Sensors and Commercial Power-Quality Analyzers for Intermittent Stator Fault Characterization

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Within the scope of predictive and preventive maintenance in industrial environments, fault detection in three-phase induction motors is crucial to reduce and, in many cases, prevent downtime and operational losses. Therefore, this work focuses on intermittent stator inter-turn short circuit anomalies, which can remain undetected by conventional monitoring systems due to their sporadic occurrence and weak signatures. In this sense, the main objective is to evaluate the sensitivity of low-cost piezoelectric sensors in com-

parison with power quality analyzers (PQAs) for the identification and characterization of stator faults under different operating conditions. The experimental campaign consisted of subjecting a three-phase induction motor to controlled insertion of a purely resistive impedance into the stator windings, enabling repeatable fault emulation. Different fault severities were reproduced through frequency modulation to generate intermittent short circuit patterns. Data were acquired simultaneously using piezoelectric sensors and a PQA. After the measurements, the recorded signals are processed using time–frequency signal processing techniques to compare the effectiveness of electrical variables and acoustic emission features extracted from both sensing technologies. Finally, preliminary results indicate that the proposed processing strategy enables low-cost piezoelectric sensors to detect inter-turn short circuit faults with satisfactory performance when compared with established power quality analyzers, supporting their potential as a cost-effective alternative for industrial condition monitoring applications.

2.12. Identification of Process Indices in Elastic Emission Machining Using Piezoelectric Diaphragm (PZT) Sensors

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Introduction: Efficient detection of subsurface damage (SSD) is essential to ensure the service life and performance of machined components, yet conventional identification methods are predominantly destructive. Elastic Emission Machining (EEM) stands out as a non-contact process that removes material at the atomic scale through chemical reactions, producing mirror-like finishes. This technique can be utilized for SSD detection by generating spherical cap-shaped imprints that allow access to and evaluation of the material's integrity below the surface. Methods: This study presents an experimental analysis of the EEM process on glass specimens using piezoelectric diaphragm (PZT) sensors for in situ signal acquisition. A 2^{k-p} fractional factorial design was implemented to evaluate the influence of variables such as tool rotation (47 to 67 Hz), tool material hardness, tool finish (CNC vs. ultra-precision), applied load (260 and 520 g), and testing time. Signals were processed using Fast Fourier Transform (FFT) and Root Mean Square (RMS) analysis to extract quantitative process indices. Results: The results demonstrated that the tool's surface finish is directly transferred to the workpiece, altering the texture of the generated caps. Frequency analysis revealed that most caps presented predominant peaks in the 20 to 32 Hz range. Notably, for tool rotations above 60 Hz, the highest peak frequency shifted to the 31–33 Hz range, or approximately 2512 Hz. Furthermore, trials that exhibited peaks at higher frequencies were correlated with lower average RMS values. Conclusions: The use of PZT sensors proved to be an effective and low-cost method for monitoring the EEM process. The generated indices successfully correlate acoustic signal characteristics with machining parameters, providing a solid perspective for future subsurface integrity characterization.

2.13. Imperfection Modelling in Fault-Tolerant System Design

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In high-stress or crisis-driven engineering contexts, system design often defaults to idealized targets of perfection. Yet, resource limitations, time pressure, and incomplete information frequently prevent such targets from being achieved, resulting in increased cognitive load, rising error rates, and brittle system behavior. This paper critiques the dominant perfection-orientated paradigm in crisis engineering and proposes an alternative approach: designing with imperfection tolerance as a primary design constraint.

Instead of attempting to eliminate all uncertainty, the proposed framework introduces the concept of imperfection budgeting, wherein acceptable degrees of fault, performance degradation, or incomplete coverage are explicitly defined and tracked from the outset. Crucially, the study does not prescribe a fixed metric for imperfection. Rather, it introduces a multi-dimensional space for imperfection modeling, covering multiple quality-related dimensions such as functional deviation, recoverability from faults, detectability of anomalies, and system stability, which can be modeled through tolerance bands, threshold-based metrics, or qualitative categorization depending on system context.

Moreover, this imperfection-tolerant perspective aligns closely with the design logic of modern AI systems, which inherently operate under probabilistic reasoning and imperfect information. AI models, particularly those based on machine learning, do not guarantee deterministic outputs; they rely on statistical inference, often exhibiting uncertainty and error margins in real-world conditions. By acknowledging and managing these imperfections as intrinsic characteristics rather than anomalies, the proposed framework supports more transparent, resilient, and adaptive system design, whether in human-controlled crisis settings or AI-driven autonomous environments.

By shifting the focus from eliminating failure to managing it, this tolerance-based approach enables more resilient, transparent, and decision-friendly engineering under non-ideal conditions.

2.14. Low-Complexity Vibration-Spectrum Feature Learning for Early-Stage Inter-Turn Short-Circuit Diagnosis in Three-Phase Induction Motors

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Three-phase induction motors are the most widely used electrical machines in industrial applications worldwide due to their robustness, low cost and reliability. Inter-turn short-circuit faults represent one of the most critical incipient failure modes in these machines and can lead to severe performance degradation if they are not detected at an early stage. Although vibration-based condition monitoring techniques have shown promising results, many recent approaches rely on complex time–frequency representations and deep learning models, which increase computational cost and implementation complexity. Therefore, a lightweight and interpretable fault diagnosis framework based on vibration signals is proposed, combining frequency-domain feature extraction and a multilayer perceptron classified. In this work, vibration signals measured by MEMS accelerometers were segmented and processed using the Fast Fourier Transform. From the resulting spectra, a compact set of spectral features, including energy, spectral centroid, bandwidth, kurtosis and skewness, was extracted and used as input to the lightweight multilayer perceptron network. Also, the method was evaluated under healthy operating conditions and multiple inter-turn short-circuit fault scenarios, considering different phases and fault severity levels. Model performance was assessed using accuracy, precision, recall, F1-score and confusion matrix analysis, along with an evaluation of preprocessing, training and inference times. The results demonstrate that the proposed FFT-based MLP framework achieves competitive classification performance while significantly reducing computational complexity when compared to deep learning approaches. These findings indicate that frequency-domain statistical features combined with shallow neural networks provide an effective and efficient solution for vibration-based inter-turn short-circuit fault diagnosis in three-phase induction motors.

2.15. Neuro-Adaptive Machines: An Edge-Intelligent Framework for Real-Time Condition Monitoring and Self-Optimizing Control

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Modern electromechanical systems increasingly operate in dynamic, uncertain environments where conventional control and monitoring pipelines are insufficient for ensuring reliability, efficiency, and autonomy. Most existing approaches treat condition monitoring and control as isolated processes and rely heavily on static models and offline analysis. This paper introduces a unified neuro-adaptive machine framework designed to endow machines with real-time perception, health awareness, and self-optimizing control capabilities directly at the edge.

The proposed architecture integrates multi-modal sensor fusion (vibration, acoustic, thermal, and electrical signals) with a lightweight deep learning pipeline deployed on embedded hardware. A sparse neural representation layer performs continuous feature extraction, while a continual learning module tracks machine state evolution and detects emerging fault patterns. These learned health states are coupled with a predictive control module that dynamically adjusts operating parameters to mitigate degradation. Drift-aware training and incremental updating enable the system to adapt autonomously to changing operating conditions without cloud dependency.

Experimental evaluation on an electromechanical test platform demonstrates that the framework achieves earlier fault detection, higher diagnostic accuracy, and faster adaptation to unseen anomalies compared to traditional signal-processing-based monitoring and fixed-parameter control strategies. The system also exhibits improved operational stability and measurable gains in energy efficiency through health-aware control adjustments.

The results validate the feasibility of embedding neuro-adaptive intelligence directly into machines to move from passive monitoring toward proactive, self-optimizing operation. The proposed framework offers a scalable pathway toward cognitive electromechanical systems, contributing to advances in automation, condition monitoring, and intelligent machine design.

2.16. Optimization Techniques for Convolutional Neural Network Architectures Applied to PMSM Motor Diagnostics

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Currently, techniques for diagnostics of the stator winding faults in Permanent Magnet Synchronous Motors (PMSMs) increasingly rely on deep learning models, particularly Convolutional Neural Networks (CNNs), due to their ability to directly process diagnostic data and detect patterns indicative of faults. However, many CNN architectures proposed in the literature are highly complex, with an excessive number of neuron connections that exceed the requirements of the specific fault detection tasks. This complexity can negatively impact the practical implementation and real-time application of such systems.

In this study, we present an optimization approach to reduce the number of connections in a CNN applied to PMSM fault detection and classification. The proposed optimization algorithm utilizes information about the correlation between automatically extracted fault symptoms at different layers of the network. By evaluating the statistical repeatability of features within the network's architecture, the algorithm selectively eliminates redundant connections and neurons that do not contribute significantly to the fault detection process.

As a result, the optimized CNN requires fewer parameters while maintaining high classification accuracy. This reduction in network complexity also leads to improved response speed, which is crucial for real-time monitoring of PMSM motors. The proposed method ensures that the diagnostic system can quickly identify and classify faults in the stator, enabling more efficient maintenance and reducing the risk of motor failure. The results demonstrate the effectiveness of the optimization technique in both improving performance and enhancing the practical feasibility of CNN-based diagnostic systems for PMSM motors.

2.17. Performance Comparison of MobileNetV1 and MobileNetV3-Small for Tool Classification in Memory-Constrained Embedded Systems

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The deployment of computer vision models on resource-constrained hardware, such as the ESP32 microcontroller, requires a critical balance between classification accuracy and memory footprint. This study investigates the performance of MobileNetV1 and MobileNetV3-Small architectures in scenarios characterized by limited data, aiming to identify the most efficient configuration for mechanical industrial tool classification. A dataset containing 106 images across five distinct classes was developed, utilizing an 80/20 train–test split with an additional 15% of training data reserved for validation. Both architectures were implemented using transfer learning with frozen ImageNet backbones and custom classification heads. MobileNetV1 was configured with a width multiplier of $\alpha = 0.25$ to aggressively reduce filters, while MobileNetV3-Small employed $\alpha = 1.0$ in "minimalistic" mode to exclude high-latency activation functions and attention modules. Both models were optimized using the Adam optimizer and categorical cross-entropy loss to ensure a controlled experimental comparison. Experimental results demonstrate that both architectures achieved equivalent performance, with a global accuracy of 91% and a weighted F1-score of 0.91. Confusion matrix analysis revealed that errors were primarily confined to visually similar classes, such as Allen keys and screwdrivers. However, a significant disparity emerged regarding model size: MobileNetV1 produced a 1.1 MB binary, whereas MobileNetV3-Small resulted in 2.1 MB, a nearly 90% increase in storage requirements without any gain in predictive performance. This research concludes that increased architectural complexity does not inherently translate to superior performance in small-data regimes. For memory-constrained devices like the ESP32, the scaled-down MobileNetV1 provides a superior cost–benefit ratio, maintaining high accuracy with a substantially smaller memory footprint. The findings highlight the necessity of prioritizing structural simplicity over architectural novelty when designing deep learning solutions for embedded AI applications.

2.18. Predictive Maintenance and Fault Detection for Motor Drive Control Systems in Industrial Robots Using CNN–RNN-Based Observers

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The condition monitoring and early fault diagnosis of motor drive systems play a critical role in ensuring the reliability and availability of industrial robots operating in smart manufacturing environments. Motor drives in robotic applications are exposed to nonlinear dynamics, variable mechanical loads, and progressive degradation, which significantly limit the effectiveness of conventional model-based fault detection and diagnosis (FDD) methods due to parameter uncertainty and unmodeled dynamics. This paper proposes a data-driven fault detection framework based on a hybrid Convolutional Neural Network–Recurrent Neural Network (CNN–RNN) observer for the continuous condition monitoring of motor drive control systems in industrial robots. The CNN component enables the automatic extraction of fault-sensitive features from multichannel sensor signals, while the RNN component captures temporal dependencies associated with fault evolution and degradation processes. The observer-based structure allows residual-like information to be implicitly learned from operational data without requiring an explicit analytical model of the system. The esults demonstrate that the proposed CNN–RNN observer achieves a fault detection accuracy of 98.4%, outperforming conventional observer-based diagnostic approaches by 12.5%. Moreover, incipient faults are reliably detected up to 350 operating hours prior to critical failure while maintaining a false-positive rate below 1.2%. These results confirm the effectiveness of deep learning-based observers as a practical solution for the condition monitoring and predictive maintenance of motor drive systems in industrial robotic applications.

2.19. Predictive Maintenance in SMT Machines Using Electrical Multiparameter Sensors and Hybrid Machine Learning Models

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Surface-Mount Technology (SMT) manufacturing demands high operational reliability, as unexpected failures lead to costly production downtime. Predictive maintenance based on continuous sensor monitoring has emerged as a promising approach to anticipate failures; however, its effectiveness depends on robust and stable anomaly detection systems. In this industrial context, anomaly detection faces specific challenges, including the absence of labeled data for supervised training, the presence of multiple operational regimes with distinct electrical characteristics, and the need for temporal stability in alarm generation. Traditional global methods such as Isolation Forest, One-Class SVM (OCSVM), and Local Outlier Factor (LOF) assume a single operational context, failing to adapt detection behavior across different regimes and often producing unstable alarms that undermine system reliability.

This work proposes a hybrid, context-aware approach that combines K-Means clustering for the automatic segmentation of operational regimes with cluster-specific Isolation Forest models for anomaly detection. The method was validated using 47,493 samples of electrical sensor data (15 variables) collected over three months from an SMT insertion machine operating in a real production environment. The proposed approach was compared against three baselines: global Isolation Forest, K-Means with OCSVM, and K-Means with LOF. Performance was evaluated in terms of regime separability (Silhouette score), temporal stability (coefficient of variation), and anomaly score consistency (interquartile range).

The hybrid method identified three distinct operational contexts, achieving 53% higher separability than the global approach (Silhouette 0.63 vs. 0.41) and 37% greater temporal stability compared to global Isolation Forest (CV 0.96 vs. 1.52), effectively reducing erratic alarm peaks. Score consistency was substantially higher than OCSVM-based clustering (IQR 0.10 vs. 5.31), while maintaining an equivalent detection rate of 1.0%, confirming that performance gains arise from contextual adaptation rather than sensitivity increase.

These results demonstrate that adapting anomaly detection to operational regimes provides a methodological advantage for industrial predictive maintenance, balancing temporal stability and sensitivity in continuous monitoring.

2.20. ProGas-Mine System: Proactive Gas Hazard Monitoring in Underground Mining Using Low-Power Long-Range Wireless Sensors

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Underground mining environments pose significant safety risks due to the accumulation of toxic and explosive gases, necessitating the use of reliable and continuous monitoring systems. However, wired system configurations, complex maintenance, and incomplete spatial coverage have limited the implication of conventional methods, which hinder real-time data transmission during critical events, thereby increasing risks to miners and delaying emergency response. Herein, a ProGas-Mine System, a low-power, multi-node wireless sensor system, was developed to enable continuous and real-time monitoring of hazardous gases in underground mines, which can communicate over a long range. The proposed system integrates distributed sensor nodes equipped with gas sensors for methane (CH_4), carbon monoxide (CO), and hydrogen sulfide (H_2S), as well as temperature and humidity sensors. The incorporated Long Range (LoRa) wireless communication ensured reliable data transmission under challenging subterranean conditions. DC–DC switching converters and a battery fuel-gauge-based power management system were further developed to enable the system to operate in an energy-efficient manner. The technical functionality and real-time performance of the system were experimentally validated in a large-scale commercial graphite mine, precisely demonstrating accurate, stable, and continuous sensing of gas concentrations and environmental parameters. Moreover, the results revealed that the system exhibits strong responsiveness, capturing real-time variations in gas levels that correlate closely with the mine ventilation cycles. Accordingly, the developed system provides a scalable and cost-effective alternative to traditional monitoring methods, facilitating a transition from reactive safety measures to proactive and predictive risk management in underground mining environments.

2.21. Self-Learning Condition Monitoring Systems for Adaptive Fault Diagnosis in Dynamic Operating Environments

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Industrial and infrastructure systems increasingly operate in dynamic environments characterised by fluctuating loads, changing operating modes, and varying environmental conditions. These non-stationary behaviours challenge conventional condition monitoring and fault diagnosis approaches, which typically rely on static models, fixed thresholds, or pre-defined fault signatures. As operating conditions evolve, such approaches often suffer from reduced diagnostic accuracy and increased false alarm rates. Self-learning condition monitoring systems offer a promising pathway toward adaptive and resilient fault diagnosis in such dynamic operating environments. This study proposes a self-learning condition monitoring framework that continuously adapts to changing system behaviour through online and incremental learning mechanisms. The framework integrates multi-sensor data streams with adaptive machine learning techniques capable of updating feature representations, decision boundaries, and fault models in real time. By combining unsupervised anomaly detection with semi-supervised learning, the system can identify emerging degradation patterns and previously unseen fault modes while maintaining robustness to normal operational variability. A key contribution of the proposed approach is its ability to differentiate between benign operational changes and true fault-related anomalies. Context-aware feature extraction and adaptive thresholding are employed to reduce false alarms under varying load and environmental conditions. Feedback loops are incorporated to refine diagnostic confidence and improve model performance as new data become available, enabling the system to learn continuously from operational experience. Illustrative case studies demonstrate that the self-learning framework achieves improved fault detection accuracy, enhanced adaptability, and lower false alarm rates compared to traditional static monitoring methods. Overall, this work highlights the potential of self-learning condition monitoring systems as a foundation for intelligent, autonomous fault diagnosis, supporting reliable and efficient operation of complex assets in highly dynamic operating environments.

2.22. The Influence of Operating Conditions and Measurement Duration on the Quality of Bearing Fault Information in Motor Fault Diagnostic Applications

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Electric motor diagnostic systems dedicated to rolling bearing fault detection impose specific signal processing requirements to ensure high effectiveness in technical condition assessment. In the case of mechanical faults, the most critical requirements include relatively long measurement durations, stable operating conditions, and high measurement accuracy. However, such conditions are difficult to achieve in real industrial drive systems, where transient states and variable operating conditions are common. Consequently, there is an increasing demand for fast and reliable fault detection methods based on the shortest possible data records.

This study investigates the influence of the data acquisition system and operating conditions on the quality of fault-related information in the rolling bearing diagnostics of induction motors. The primary objective is to determine the minimum measurement duration that enables reliable fault detection while preserving essential diagnostic features.

Experimental investigations were conducted for various types and severities of rolling bearing damage under both steady-state and transient operating conditions. To enable fully automated classification, a shallow neural network was employed. Specifically, a classifier based on Kohonen Self-Organizing Maps (SOMs) was used, with input features extracted from measurement signals using envelope spectrum analysis and selected statistical indicators.

The results demonstrate that the quality of fault-related information strongly depends on both the measurement duration and the operating conditions of the motor. Reducing the data vector length significantly degrades diagnostic performance, particularly under dynamic operating conditions. The obtained results highlight the importance of appropriate measurement duration selection in the design of fast and practically applicable diagnostic systems for induction motor bearing fault detection.

2.23. Ultrasound Condition Monitoring of Existing Imperfections in Static Equipment

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Continuous operation of static equipment is not possible without assessing the metal condition, and one method to implement the asset management strategy is ultrasonic (UT) analysis of existing imperfections. A focus is placed on the risk-based inspection (RBI) of a high-pressure amine absorber in service where a zone with permissible short, scattered indications is found before the commissioning. The vessel has been hydrotested and put into operation, and the corresponding risk category has been defined. It has been in service for ten years, with regular thickness measurements and maintenance performed. The subsequent scheduled inspection is set at every five years. Initially, RBI recommendations are followed based on the criticality of the asset and the severity evaluation of the imperfections. For an absorber made from P355NH with a height of roughly 17 m and a diameter more than a meter, shell metal UT zones of a total size of 2.115 m^2 have been evaluated. No crack-like faults have been detected, and the existing rounded imperfections with a diameter of less than 4 mm are being monitored for eventual growth. Since no change is observed after the strategy-defined five-year period and all the inspection protocols show consistent results, an RBI reevaluation is performed for the definition of the new risk category. As a result, there is a decrease in the calculated risk of the corresponding asset.

Funding: The author acknowledges support from project BG16RFPR002-1.014-0005.

3. Machines Design and Additive Manufacturing

3.1. Structural and Optical Optimization of SiC Nanotube-Reinforced PVP Nanocomposites for Advanced Functional Applications

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Silicon carbide (SiC)-based polymer nanocomposites have attracted significant attention for advanced electromechanical and optoelectronic applications due to their thermal stability, mechanical robustness, and tunable electronic properties. In this study, one-dimensional SiC nanotubes were successfully synthesized via a high-temperature carbothermal method at 1800 °C and subsequently incorporated into a polyvinylpyrrolidone (PVP) matrix to fabricate SiC/PVP nanocomposites with filler concentrations ranging from 1 to 5 wt%. The structural, morphological, and optical properties of the composites were systematically investigated using X-ray diffraction (XRD), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and UV–Vis spectroscopy.

SEM observations confirmed the hollow nanotube structure and rough surface morphology of SiC, while XRD analysis revealed the formation of the cubic 3C-SiC phase and its effective incorporation into the amorphous PVP matrix. At low filler loadings (1–3 wt%), SiC nanotubes were homogeneously dispersed, leading to reduced crystallite sizes, increased microstrain, and higher dislocation densities due to enhanced interfacial interactions and lattice distortion. In contrast, at 5 wt% SiC, aggregation effects became dominant, resulting in increased crystallite size and reduced lattice defects. Optical measurements demonstrated a non-linear band gap behavior, with a minimum value of 5.51 eV observed at 3 wt% SiC/PVP, attributed to interface-induced defect states and enhanced electronic interaction. FTIR spectra further confirmed strong interfacial bonding between SiC surface groups and PVP functional groups.

Based on the combined structural and optical analyses, an optimal filler concentration of approximately 2 wt% was identified, offering balanced crystallinity, defect density, and band gap tunability. These findings highlight the potential of SiC/PVP nanocomposites as promising materials for high-performance optoelectronic and dielectric components in advanced engineering systems.

3.2. CABLEAnkle: A Cable-Driven Approach to Assisted Ankle Rehabilitation

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Introduction: Effective rehabilitation of the ankle joint is critical for maintaining mobility and functional independence, particularly among elderly individuals and patients undergoing post-injury or post-surgical recovery. Many existing robotic rehabilitation devices rely on rigid mechanical architectures, which may increase weight, reduce adaptability, and compromise user comfort. Cable-driven actuation offers a flexible and lightweight alternative, capable of safely assisting complex joint motions. This work introduces CABLEAnkle, a cable-driven device developed to support assisted and rehabilitative ankle movements.

Methods: CABLEAnkle consists of a foot-shaped platform actuated by four Dynamixel servo motors that modulate cable tension routed through a knee-mounted brace. The mechanical architecture is designed to reproduce the three primary rotational degrees of freedom of the ankle: dorsiflexion/plantarflexion, inversion/eversion, and adduction/abduction. A detailed CAD model was developed to define geometry, cable routing, and motor placement. Kinematic modelling was carried out to relate motor rotation to cable length variation. Finite element analysis was performed to assess the structural feasibility of a lightweight PMMA foot platform under representative loading conditions. A preliminary prototype was then assembled.

Results: The kinematic analysis confirmed that coordinated cable actuation enables physiologically relevant ankle rotations. Structural simulations demonstrated that a 5 mm thick PMMA platform withstands symmetric and asymmetric loads representative of assisted ankle motion without exceeding material stress limits. The assembled prototype successfully reproduced the intended ankle movements, validating the feasibility of the proposed mechanical and actuation design.

Conclusions: The results demonstrate that CABLEAnkle is a compact, lightweight, and adaptable cable-driven solution capable of replicating essential ankle kinematics. The proposed design provides a promising foundation for future experimental validation and clinical evaluation in rehabilitative and assistive applications.

3.3. Super Austenitic Stainless Steel with SiC Metal Matrix Composites for Nozzles in Harsh Environment

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We investigated the possibility of developing super austenitic stainless steel Avecta SMO 254 X1NiCrMoCuN20-18-7 (EN 10088-4) and austenitic stainless steel X15CrNiSi25-21 (EN 10095) coated with SiC, resulting in the obtainment of a Metal Matrix Composite (MMC) by Additive Manufacturing (AM) for the upgrade of nozzles for sulphur recovery thermal reactors. One layer of the MMC targets the outer surface of the part that is in constant contact with the flame and the area is subjected to high friction erosion. The Directed Energy Deposition Laser (DED-LB) method has made it possible to produce a high strength-to-weight ratio. The aim is to engage lower-cost material with similar thermal stability and durability in extreme conditions. The robotic unit used for the application allowed for the computer control of the positioning, feeding of the SiC particles inside the shielding gas and deposition in the melted pool. After the solidification process, visual testing (VT) and ultrasonic testing (UT) were applied for the non-destructive evaluation, checking for disbonding and subsurface imperfections. Then, samples were tested with microhardness measurements, bond strength, microcracking detection, porosity, interface zone assessments and microstructural analysis. The process achieved 0.4 to 0.7 KJ/mm heat input with no defects and the intended nozzle surface passed UT and VT. Controlled parameters provided strong metallurgical bonding.

Funding: The author acknowledges support from project BG16RFPR002-1.014-0005.

3.4. AGWO-Optimized xLSTM Model for Thermal Error Prediction in CNC Machines Using Multi-Sensor Temperature Data

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Thermal deformation is a major source of positioning error in CNC machines due to nonuniform heat generation and complex temperature variations across different machine components. Accurate prediction of thermal error is challenging because temperature data collected from multiple sensors exhibit nonlinear, noisy, and long-term dependent behavior. In this work, a thermal error prediction framework is proposed using an extended Long Short-Term Memory (xLSTM) network, where critical model hyperparameters are optimized using an Adaptive Grey Wolf Optimizer (AGWO) before model training. The bio-inspired AGWO algorithm adaptively balances exploration and exploitation by dynamically adjusting its control parameters, enabling efficient global search of the hyperparameter space. Temperature data acquired from multiple sensors placed at different locations of the CNC machine are used as input features to capture spatial and temporal thermal effects. The optimized hyperparameters are then employed to train the xLSTM model using gradient-based learning. Experimental results demonstrate that the AGWO-optimized xLSTM model achieves significantly lower thermal prediction error compared to conventional manually tuned and gradient-only approaches. The proposed method improves prediction accuracy, convergence stability, and generalization capability, making it suitable for real-time thermal error compensation in high-precision CNC machining applications. After compensating for the thermal error, the diametral deviation reduces to 95% and improves the thermal stability of the machine tool. The prediction model capability is proven to be improved using the proposed approach.

3.5. Benchmarking Electrical Resistance Measurement Methods for Piezoresistive 3D-Printed Polymer Composites

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Accurate measurement of electrical resistance is a critical requirement in the characterization of piezoresistive polymer composites, particularly when resistance variations induced by mechanical deformation are small relative to the nominal resistance value. This challenge is especially relevant for conductive polymers produced by additive manufacturing (AM), where contact resistance, material anisotropy, and process-induced variability can significantly affect measurement reliability. This paper presents a methodological review and benchmarking of electrical resistance measurement techniques applicable to piezoresistive 3D-printed polymer composites. Classical approaches, including two- and four-point measurements, Wheatstone bridge configurations, and Kelvin-based techniques, are reviewed and compared in terms of accuracy, sensitivity, robustness to parasitic resistances, and experimental complexity. Beyond conventional methods, the paper discusses the potential of recent and emerging measurement strategies, such as advanced bridge configurations, digitally assisted techniques, and hybrid analog–digital approaches enabled by modern data acquisition systems and embedded electronics. Although not exhaustively implemented, these approaches are considered to frame current trends and future directions in high-resolution resistance measurement for self-sensing materials. Analytical formulations and circuit-level models are employed to describe the operating principles of the reviewed methods, supported by simplified electrical simulations using accessible electronic circuit simulators. In parallel, a concise overview of commercially available measurement hardware—including precision source–measure units, data acquisition systems, and instrumentation amplifiers—is provided to contextualize practical implementation choices. The comparative analysis indicates that the four-point measurement method constitutes a robust and practically viable reference approach for detecting small resistance variations in conductive AM polymers within typical laboratory constraints. Rather than establishing a definitive hierarchy among techniques, this work positions the four-point method as a justified baseline for comparison. Overall, the proposed benchmark combines theory, simulation, and hardware considerations, offering practical guidance for experimental design while leaving scope for future investigation of emerging measurement techniques and recent developments in resistance sensing for self-sensing AM materials.

3.6. Comparative Assessment of Drive Power Demand in Vibratory Technological Equipment Equipped with Planetary, Differential, Double Crank–Slider, and Cam-Type Vibration Exciters

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Introduction. Vibratory technological equipment is widely employed for conveying, screening, compaction, and surface-treatment operations, where drivetrain sizing is dictated by peak power and torque and their pulsations. Prior studies predominantly report dynamics of individual vibration exciters and frequently rely on mean-power or linearized harmonic estimates, which prevents a like-for-like comparison of drive power demand across exciter architectures under identical vibration output and process loading. This study addresses these gaps by introducing a unified comparative framework for planetary, differential, double crank–slider, and cam-type exciters.

Methods. A unified kinematic-dynamic model was formulated in generalized coordinates for each vibratory system. Instantaneous drive torque was obtained from the balance of inertial forces, suspension elastic–damping reactions, and technological resistance forces mapped through mechanism-specific transmission ratios. Instantaneous mechanical power demand was evaluated as $P(t) = M(t) \cdot \omega(t)$. To enable a fair comparison, all mechanisms were assessed over a common operating set (target vibration amplitude and frequency, payload mass, and technological resistance characteristics). Evaluation metrics included mean and peak power demand, peak torque, and power pulsation index (peak-to-mean ratio), supplemented by decomposition of inertia-driven versus process-driven contributions.

Results. The framework produces power demand maps that reveal pronounced mechanism-dependent power pulsations that would be underestimated by average power methods. For the same vibration output, planetary and differential exciters exhibit lower peak power demand and reduced torque ripple, whereas cam and double crank–slider exciters show higher peaks and pulsation indices due to more non-sinusoidal motion. Mean power demand is primarily governed by payload and technological resistance, while kinematic nonlinearity largely determines peaks and pulsations.

Conclusions. The proposed framework is novel in providing an objective, harmonized, multi-metric comparison of drive power demand across distinct exciter mechanisms, extending beyond conventional averaged and linearized assessments. It enables evidence-based exciter selection and drivetrain sizing to improve energy performance and durability of vibratory technological equipment.

3.7. Design and Structural Assessment of a Modular Vision Module for Deep-Water Robotic Manipulation

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The expansion of subsea industrial activities has increased the demand for reliable robotic systems capable of performing inspection and intervention tasks in deep-water environments. In particular, the integration of high-performance vision systems into autonomous and remotely operated underwater platforms remains a critical engineering challenge due to severe hydrostatic pressure, hydrodynamic loading, and space constraints imposed by robotic manipulators. This work presents the conceptual development, mechanical design, and structural validation of a compact underwater vision module intended for deployment on a robotic arm operating in offshore environments. A systematic engineering design methodology is adopted, beginning with requirement definition and concept generation, followed by a comparative evaluation of alternative configurations using a structured materials and design selection framework. The selected concept is subsequently refined through detailed mechanical design, including material specification, geometric optimization, and sealing strategy definition. Structural integrity is assessed through numerical simulations based on the finite element method, accounting for external pressure loads representative of deep-sea operation. In addition, fluid–structure interaction effects are indirectly evaluated through dynamic analyses aimed at minimizing hydrodynamic resistance. The numerical results confirm that the proposed housing maintains structural safety at operational depths up to 300 m, while achieving a substantial reduction in hydrodynamic loading relative to a previous design generation. The developed solution demonstrates improved robustness, compactness, and hydrodynamic efficiency, supporting its suitability for integration into underwater robotic manipulation systems.

3.8. Development and Validation of an Automatic Bending Follower Device

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The metalworking industry plays a decisive role in the economy. Among the various metal-forming processes, sheet metal bending is essential due to its ability to produce bends with high precision and structural strength. However, the bending quality depends not only on the performance of the bending machine but also on the correct stabilisation of the sheet during the process. In this context, sheet followers are essential auxiliary equipment, designed to accompany the upward movement of the sheet. The main objective of this work was to develop a new sheet follower model, capable of replacing the equipment currently used in a given company. The aim was to design a robust and functional solution that would accurately follow the natural movement of the sheet metal during the bending operation, ensuring operator safety and material integrity. To this end, mechanical design concepts, CAD tools, and structural and kinematic dimensioning methodologies were integrated, as well as the careful selection of materials and manufacturing processes. In addition, the drive system was analysed, costs were estimated, and the proposed solution was compared with competing equipment on the market. This work also aimed to reinforce technical knowledge in the area of auxiliary tilting devices by identifying technological trends and proposing a viable and optimised solution. As a result, the developed bending monitor fully complies with the defined requirements and limitations and demonstrates high functionality and performance. The solution presented is economically more advantageous than the equipment currently in use, without compromising the reliability and accuracy of the process. Thus, all the established objectives were fully achieved, validating the proposal as an effective and competitive alternative for industrial application.

3.9. Development of Multifunctional Composite Sandwich Panels: Process and Optimization

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Introduction: The most common processes for the production of multifunctional composite sandwich panels include vacuum-assisted hand lay-up, vacuum infusion, among others. However, these processes are very human-dependent, especially vacuum-assisted hand lay-up. This work aims to develop, optimize, and validate a controlled vacuum infusion manufacturing process for multifunctional composite sandwich panels, enabling scalable, efficient, and high-quality production while improving mechanical performance and process consistency.

Methods: The developed equipment incorporates dual heated plates operating at temperatures up to 200 °C, segmented thermal zones, and a vertical actuation system to ensure uniform pressure during processing. It enables the manufacture of panels measuring up to 1.0 m × 2.0 m × 0.2 m and can be reconfigured into a 2.0 m × 2.0 m working surface through a rotatable upper plate, enhancing operational flexibility. This configuration allows for the single-step production of sandwich panels via vacuum infusion, significantly reducing production time. Curing cycles were optimized using Differential Scanning Calorimetry (DSC) in accordance with ASTM D3418, considering the limitations of the raw materials. Sandwich panels incorporating glass or basalt fibres, an epoxy matrix, and an extruded polystyrene (XPS) core were produced and evaluated. A comprehensive experimental campaign, including DSC, Barcol hardness, density, fibre and void content, flexural performance, and dimensional stability tests, was conducted following relevant international standards.

Results: The results indicate that sandwich panels manufactured with basalt fibres using the vacuum infusion process exhibit superior overall performance. Additionally, vacuum infusion enables faster and more consistent production compared to vacuum-assisted hand lay-up.

Conclusions: The validated infusion strategy and control system demonstrate strong potential for scalable manufacturing, with further work planned to complete performance validation and refine process optimization.

3.10. Experimental and Analytical Investigation of Infill Pattern and Build Orientation Effects on the Flexural Strength of FFF-Printed PLA Components

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Fused Filament Fabrication (FFF) is without a doubt the most widely adopted additive manufacturing method for polymer components. As in every additive manufacturing process, the mechanical performance of manufactured components is a result of process parameters and design considerations. These include the infill pattern and parameters, the build orientation, and the temperature and layer height, amongst others, and all play a significant role in the flexural, tensile and compression properties of components. The present study aims to uncover the underlying mechanisms behind the performance of FFF-manufactured components using a combination of analytical and experimental methods to understand the developed stresses on components and the failure mechanisms of said components.

The performance of additively manufactured components was evaluated using a standardised 3-point bending setup both in the numerical and experimental domains. Three-point bending tests were conducted in accordance with relevant standards to evaluate flexural strength and stiffness. Standardised test specimens from polylactic acid (PLA) were deposited with varying infill patterns and build orientations whilst keeping all other parameters stable. The results of the experimental campaign were combined with analytical modelling (based on classical beam theory) and finite element modelling to achieve an all-round view of the performance of components.

3.11. Experimental Assessment of Piezoresistive Self-Sensing Capability in 3D-Printed Conductive PLA Specimens

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Additively manufactured conductive polymers enable the development of material specimens with an intrinsic sensing capability, where mechanical loading can be inferred directly from electrical response without the use of discrete sensors. Among these materials, carbon-filled conductive polylactic acid (PLA) filaments provide a low-cost and accessible platform for exploring piezoresistive self-sensing concepts at the material level. This work presents an experimental assessment of the piezoresistive self-sensing capability of 3D-printed conductive PLA specimens manufactured by material extrusion. Standard tensile specimens were produced and subjected to uniaxial loading using a universal testing machine, while the electrical resistance was monitored simultaneously during mechanical deformation. The experimental study focuses on verifying the existence, stability, and repeatability of the electromechanical response within the elastic deformation regime. The results reveal a clear and consistent correlation between applied mechanical loading and electrical resistance variation, with resistance changes closely following the imposed deformation cycles. This behavior confirms that the printed conductive PLA specimens exhibit a stable piezoresistive response suitable for strain-dependent signal acquisition at the material level. Rather than pursuing a comprehensive material characterization, this study provides a proof of concept demonstrating the feasibility of using 3D-printed conductive PLA specimens as self-sensing material elements. The findings contribute experimental evidence supporting the use of additively manufactured piezoresistive polymers as embedded sensing media in future mechanically loaded components and robotic structures.

3.12. Fan-Type Inducer for a Centrifugal Pump with Multi-Material Blades Made of Stellite 6 and SST 316L Additively Fabricated Using Wire Arc Additive Manufacturing

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The value of applying wire arc additive manufacturing (WAAM) to impellers, a key component of turbomachinery including pumps, has been variously discussed. WAAM is a metal additive manufacturing technology suitable for fabricating medium to large components by applying arc welding. Many of these studies are intended to fabricate components using only a single material. While welding wires for WAAM are commercially available in various materials, enabling the potential for multi-material components, research focused on industrial applications of multi-materialization has been limited. This study conducted experimental investigations aimed at extending the service life of a fan-type inducer. The inducer is an axial flow impeller attached to a centrifugal pump in order to improve pump suction performance. The service life of inducers is affected by cavitation erosion of the blades. Therefore, it is planned to use a multi-material blade combining Stellite 6, which is highly resistant to cavitation erosion, and SST 316L, a general purpose austenitic stainless steel. Two experiments were conducted. The aim of the first experiment was to evaluate mechanical properties using WAAM fabricated multi-material test specimens. The aim of the second experiment was the fabrication of an inducer with a multi-material blade using WAAM and machining. Experimental results of multi-material test specimens confirmed that the mechanical properties are suitable for industrial applications. The inductor was fabricated within industrial-grade dimensional tolerances. These results clarify that multi-material blades combining Stellite 6 and SST 316L are feasible using WAAM.

3.13. Flexural Behavior of Material-Extruded PLA Components: Analytical, Experimental and Numerical Assessment of Stiffness and Strength

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Additive Manufacturing (AM), particularly polymer 3D printing, enables the production of structural components with complex geometries; however, predicting mechanical stiffness and strength directly from manufacturing conditions remains a major challenge. In Material Extrusion (MEX) processes, as defined by ISO/ASTM standards, the layer-by-layer deposition strategy introduces process-dependent structural features that strongly influence the resulting mechanical response. This work presents an analytical, experimental and numerical investigation of the flexural behavior of PLA components manufactured by material extrusion, following ISO 178 guidelines, with the objective of linking processing characteristics to effective mechanical properties. For components subjected to bending-dominated loading, flexural response provides a representative framework to assess stiffness and strength while activating interlayer interactions that are not captured by uniaxial tests. Three-point bending experiments were conducted on specimens produced with different filament deposition orientations to validate analytically derived estimates of flexural stiffness and load-bearing capacity. Scanning electron microscopy (SEM) was used to characterize process-induced structural features, including voids, filament morphology and layer interfaces, providing a physical basis for interpreting the observed mechanical behavior. In parallel, finite element analysis (FEA) was employed to complement the experimental results by analyzing stress and shear distributions under bending. The combined analytical, experimental and numerical approach highlights the role of manufacturing-induced structure in governing flexural performance and demonstrates how process-informed modeling can be used to estimate stiffness and strength in material-extruded polymer components. The results contribute to a clearer understanding of process–structure–property relationships in additive manufacturing and support the development of predictive mechanical descriptions for 3D-printed structures, reducing reliance on extensive experimental testing.

3.14. Intelligent Hybrid Manufacturing with Real-Time Defect Monitoring and CNN–LSTM-Based Process Control

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Hybrid manufacturing has emerged as an advanced manufacturing technique to fabricate complex, critical components with precision and ensure functional performance. Such technologies face some obstacles, such as process variability, defect formation and insufficient real-time adaptiveness. This study proposes an intelligent framework to mitigate such limitations by incorporating an ML-driven real-time monitoring tool for process control, including defect identification and quality optimisation. This approach integrates multi-sensor in situ monitoring tools during the fabrication process, such as temperature sensors, visual sensor data and process-related vibration data. A convolutional neural network (CNN) is utilised to identify spatial attributes associated with surface characteristics and defect patterns during the process. A long short-term memory (LSTM) network is employed to capture time-dependent relationships within process signals that are combined with a CNN to ensure in situ defect identification and predict process quality status, including surface integrity and trends in mechanical properties. Handcrafted statistical feature extraction and smart anomaly-driven image features inspired by activity recognition are utilised in the LSTM network to identify predefined types of anomalies. This ML-driven framework develops an adaptive control strategy to execute the real-time opitimisation of critical parameters, such as energy consumption, feed rate, heat input and tool path. Therefore, such an intelligent data-driven approach ensures defect mitigation and stabilises the process by facilitating the advanced closed-loop decision-making in hybrid manufacturing environments. Higher accuracy ensures the model's capability for in situ process monitoring and defect identification. Moreover, the proposed framework also achieves superior performance compared to conventional ML approaches. Extensive robustness checks of this proposed CNN–LSTM framework are required to adopt and implement it for large-scale industrial applications.

3.15. Investigating Human Responses to Demolition Robots in a Simulated Construction Environment

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Human–robot collaboration (HRC) is increasingly being introduced into construction and demolition activities to improve efficiency and help reduce human exposure to hazardous tasks. Construction sites pose unique hazards regarding close human–robot interaction during demolition operations. This presentation discusses the development of a simulated virtual environment designed to examine potential hazards and subsequent human responses while working alongside a demolition robot.

The study explores various risk factors that may cause operators of demolition robots to situate themselves within the hazard zone of the robot, that is, within an area near the robot where they can be hit, pinned, or crushed by any part of the robot. Consequently, the study evaluates participants' situational awareness and response to sudden and unexpected robot behaviors, including outrigger and arm swing motions, as well as structural hazards such as roof and floor collapses. While participants conduct different demolition tasks, the established virtual environment enables controlled manipulation of hazard types, environmental conditions, and spatial configurations while monitoring human perception, reaction, and decision-making under varying risk conditions. Participant responses are evaluated in terms of reaction time, spatial behavior, perceived risk, and task performance. Results from this study provide quantitative and qualitative insights into critical safety parameters for construction HRC. These findings will inform the development of preliminary safety thresholds for HRC demolition tasks, contributing to the foundation of future safety standards in construction robotics.

3.16. Investigation of Processing Parameters in Waste Material Management for FDM-3D Printing

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Fused deposition modeling is a widely used additive manufacturing technique across the globe. The method has been rapidly adopted by academia and industry for making polymeric material components for various applications. The quality of the produced parts depends on process parameters and the fabrication environment. Key process parameters, such as nozzle temperature, print speed, layer thickness, and build orientation, influence the quality of the manufactured parts. However, waste materials are generated from failed prints, support structures, and end-of-life components. Such material waste production raises concerns regarding resource efficiency as well as environmental sustainability. In this investigation, we use process parameters to find the critical factors involved in the effective management of waste materials for FDM (fused deposition modeling) additive manufacturing (3D printing) applications. We use the most common biodegradable thermoplastic polymer materials, such as polylactic acid (PLA). We also employ acrylonitrile butadiene styrene (ABS) and reinforcement-based polymer composite materials. We emphasize the collection, segregation, cleaning, shredding, and re-extrusion of wastes, giving particular attention to their influence on filament quality and printability. The fabrication step is also monitored by an in-built camera to identify any anomalies occurring during the part-making process. The findings demonstrate that tailored parameter sets are essential to mitigate common challenges like poor layer adhesion, warping, and inconsistent extrusion inherent to reprocessed materials. The research shows whether process parameters influence waste material production for a specifically designed material.

3.17. Mechanical Cad Design for Next-Generation Aerospace Structural Systems Using Advanced Material Additive Manufacturing Technology

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Next-generation aerospace platforms require structural systems with exceptional strength-to-weight ratios and reduced part counts. Unlike the capabilities of traditional subtractive techniques, AM provides us with the geometrical complexity and material structure that we require to achieve these objectives. Current mechanical CAD practices are ill-equipped to fully exploit AM's potential. The main drawbacks, including thermal distortion or anisotropic behavior, are not a concern when working with innovative new materials, like titanium alloys or high-performance materials. As a result, the components are ultimatelytoo expensive and do not meet the requirements. This research aims to create a new combined CAD-based Design for Additive Manufacturing (DFAM) that directly links a component's functional requirements with the material behavior and machine settings so that we can create advanced aerospace structural systems. Topology optimization, as an initial step in the workflow, takes aerospace load cases as input, and then we make AM constraints, such as minimum feature size and optimal build orientation. We then run FEA and thermal–mechanical AM analyses to optimize the geometry, reduce residual stresses, and conduct distortion forecasting prior to fabrication. Ultimately, when the DFAM framework is used, the average mass of our demo parts decrease by 34–38 percent compared to the initial designs. On top of this, we incorporated these do-it-right mitigation defect-reduction tricks directly into the CAD models, which cut the distortion in the post-build step by 82%. The suggested CAD-DfAM approach combines the design, material behavior, and aerospace physics of the AM process, providing us with a sound and proven method of creating lighter, more accurate, and higher-quality aerospace structural systems.

3.18. Numerical Investigation on the Influence of Recess Geometry and Restrictor Type on Hydrostatic Guideways

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Hydrostatic guideways are widely used in precision and ultra-precision machine tools due to their high load-carrying capacity, stiffness, and superior vibration isolation capabilities. This study presents a comprehensive computational fluid dynamics (CFD) investigation of the influence of different recess shapes and restrictor types on the key performance indicators of hydrostatic guideways. A three-dimensional CFD model is developed using ANSYS Fluent to simulate lubricant flow through the restrictor, recess, and land regions under steady-state operating conditions. Multiple recess geometries are analysed while maintaining a constant recess-to-land area ratio, and both capillary and orifice restrictors are modelled with appropriate flow characteristics. The performance of the hydrostatic pad is evaluated in terms of recess pressure, load- carrying capacity, stiffness, and mass flow rate over a range of operating fluid film thicknesses. The results indicate that recess geometry has a significant impact on pressure uniformity and load distribution, while the restrictor type plays a dominant role in overall performance. Orifice restrictors consistently exhibit higher load-carrying capacity and reduced mass flow rate compared to capillary restrictors, indicating improved hydraulic efficiency. The findings provide practical design insights for optimizing hydrostatic guideways in high-precision manufacturing and advanced machine tool applications.

Furthermore, the analysis reveals that specific recess configurations minimize flow recirculation zones, thereby stabilizing the fluid film pressure profile. This stabilization is critical for reducing micro-vibrations during machining processes. The study highlights that while capillary restrictors offer linear flow characteristics, the non-linear behaviour of orifice restrictors provides superior stiffness compensation under varying loads. Consequently, selecting an optimal recess shape with an orifice restrictor enhances damping characteristics, leading to superior surface finish quality. These numerical predictions enable designers to balance hydraulic power consumption with mechanical stability, facilitating the development of energy-efficient machine tools capable of achieving nanometric positioning accuracy in challenging, dynamic environments.

3.19. Stator Coreless Winding Performance Metrics for Electrical Machines: Implications from Previous Studies

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Coreless winding designs for stators have gained more interest in the field of electrical machine engineering because of their ability to deliver high-efficiency results, lower electromagnetic losses, and enhanced torque density. Coreless windings successfully reduce iron losses, cogging torque, and magnetic saturation effects by removing the ferromagnetic stator core, making them ideal for applications with low to high speeds and low torque ripple. This resaerch offers a detailed overview of performance metrics related to stator coreless windings, deriving insights from earlier documented analytical, numerical, and experimental research. The key performance indicators analyzed consist of electromagnetic torque capability, winding factor, harmonic distortion, copper loss, thermal behavior, power density, and overall efficiency. The impact of winding topology like toroidal, concentrated or non-concentrated, planar or flat, and printed and flexible PCB-based windings on these performance metrics is examined in depth. Moreover, practical issues concerning mechanical structural support, thermal control, insulation needs, and production tolerances are examined. Comparisons among various machine topologies and operational conditions are emphasized to uncover the inherent trade-offs between efficiency, torque density, and thermal performance. This study offers design-focused insights and highlights essential factors for enhancing stator-less machines by integrating current research results. The findings of this review aim to aid informed design choices for new applications, such as hydro or wind energy systems, electric vehicles, and aerospace propulsion and actuation systems.

3.20. The Importance of Machine Downtime in the Automotive Industry and the Impact of Improvements

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In the automotive industry, ensuring continuous production and maintaining equipment reliability are vital for meeting both quality expectations and delivery schedules. Radiator manufacturing relies heavily on core builder machines, which are responsible for assembling radiator cores with precision and consistency. Any unplanned downtime in these machines can significantly disrupt the manufacturing process, leading to production delays, increased operational costs, and potential risks to product quality.

A common challenge encountered with core builder machines is the frequent failure of their motion systems, particularly those exposed to high cycle rates and harsh working environments. For example, in one case, a belt-driven servo piston system used in a core builder machine was found to fail approximately every two months. These failures resulted in notable unplanned downtime, impacting overall production efficiency and placing additional strain on maintenance teams.

To address this issue, a practical maintenance improvement was implemented by replacing the original belt-driven servo piston system with a pneumatic piston solution. This modification aimed to enhance the reliability of the machine, reduce the frequency of unexpected breakdowns, and improve maintenance efficiency. After the change, operational data and maintenance records were reviewed to evaluate the impact on machine performance. The observations revealed that the pneumatic piston system performed more consistently under demanding conditions, leading to fewer failures, reduced downtime, and lower maintenance costs.

Overall, this study demonstrates that targeted maintenance improvements can have a positive impact on equipment reliability and production continuity in radiator manufacturing.

3.21. Topology Optimization and Additive Manufacturing of Robotic Arm Components for Structural Weight Reduction

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Additive manufacturing (AM), also referred to as Rapid Prototyping (RP), encompasses advanced manufacturing technologies that fabricate components layer by layer and has gained significant attention across diverse engineering applications. Topology optimization (TO) has emerged as an effective design approach for reducing weight while maintaining structural integrity, particularly for components traditionally produced through casting or machining. In this study, topology optimization of key robotic arm components, namely the base cylinder, lower link, and upper link, is performed to achieve substantial mass reduction. The Functional Generative Design (FGD) module is employed for topology optimization, while ANSYS Workbench is used to validate the optimized designs through structural analysis. The optimization objective targets a minimum mass reduction of 40% relative to the original designs. The optimized results demonstrate weight reductions of 73% for the base cylinder, 50.66% for the lower link, and 46.89% for the upper link, while induced stresses remain below the ultimate tensile strength of ABS material. The optimized components are fabricated using Fused Deposition Modelling (FDM) and successfully assembled. The findings confirm that the proposed approach effectively achieves significant weight reduction without compromising structural performance.

3.22. Using Differentiable Simulations for the Design of Bistable Dome Shell Structures

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Bistable dome shell structures exhibit snap-through instabilities that enable rapid shape changes and mechanical switching behavior. These elements have been reported as key components in soft valves, oscillators, and grippers, where they provide energy-efficient actuation and the ability to maintain stable configurations without continuous power input. However, their design involves facing nonlinear mechanics and high sensitivity to geometric parameters such as shell thickness, curvature, and height–radius ratio. Traditional design approaches rely on computationally expensive parametric sweeps or trial-and-error experimentation. While differentiable simulation has been successfully applied to beam-based bistable structures, its application to dome shell geometries remains less established. Differentiable simulations allow computing gradients of design objectives with respect to geometric and material parameters, enabling gradient-based optimization that can significantly accelerate the design process. In this research, an axisymmetric dome shell model under quasi-static loading conditions is used to study the existence of bistability, snap-through threshold, and force–displacement response using differentiable simulations. Key geometric parameters governing bistable behavior are identified, and their influence on snap-through characteristics is analyzed through gradient information. The results are validated against conventional finite element approaches to assess numerical accuracy and gradient reliability. The expected outcome is a set of guidelines on when differentiable simulation provides reliable gradients for bistable dome shell design, and what modeling choices are necessary to handle snap-through behavior in a stable and reproducible manner.

3.23. Using XFEM to Integrate the XIGA Method to Simulate the Stress Concentration Factor at the Circular Hole of an FGM Plate

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In recent decades, numerical methods have become indispensable tools in solving complex problems in science and engineering, where the finite element method (FEM) is widely recognized as an effective computational approach. However, the traditional FEM often encounters significant limitations in modeling discontinuities such as cracks, holes, or material interfaces, especially when dealing with functionally graded materials (FGMs). To overcome these challenges, this study introduces an advanced framework that integrates the Extended Finite Element Method (XFEM) with the Isogeometric Analysis (XIGA) approach to simulate the stress concentration factors (SCFs) around circular holes in isotropic and FGM plates. The methodology employs the level-set method to represent discontinuous boundaries and incorporates enrichment functions into the displacement field, enabling accurate modeling of stress concentrations without remeshing. MATLAB codes were developed to implement this integration, offering a flexible computational platform for practical applications. The performance of the proposed method was evaluated through several benchmark problems, including isotropic plates with circular holes near material boundaries and FGMs subjected to uniaxial loading. The results obtained by means of XFEM–XIGA were compared against analytical solutions, standard FEM, and available experimental data. For isotropic plates, the XFEM–XIGA model achieved a stress concentration error of 1.71%. For FGM plates with cracks or circular holes, the error of XFEM–XIGA was 2.55% when compared with exact solutions. These findings highlight the robustness and accuracy of the integrated method in handling complex geometries and heterogeneous material properties. Overall, this study demonstrates that the combination of XFEM and XIGA provides an efficient and reliable tool for analyzing SCFs in FGM structures, paving the way for improved modeling of industrial components where stress concentrations at material boundaries are critical to structural performance.

4. Electrical Machines and Drives

4.1. Enhanced SVPWM Strategy for Harmonic Suppression in Asymmetrical Six-Phase Induction Machines

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Introduction: Six-phase induction machines represent an evolution of conventional three-phase systems, offering enhanced reliability, efficiency, and fault tolerance. The additional degrees of freedom introduced by the six-phase configuration result in multiple orthogonal subspaces, namely the α–β plane responsible for torque production and the x–y subspace, which does not contribute to torque and is mainly associated with copper losses and harmonic components.

Methods: This work proposes an enhanced space vector pulse width modulation (SVPWM) strategy specifically developed for asymmetrical six-phase induction machines. The proposed approach enables accurate synthesis of the reference voltage vector in the α–β plane while ensuring zero average voltage injection in the x–y subspace for any angular position. Unlike virtual-vector-based modulation techniques reported in the literature, the proposed strategy is not restricted to specific sectors or angular regions and is applicable over the entire range of reference voltage vector magnitudes.

Results: The effectiveness of the proposed SVPWM strategy was first assessed through simulation and subsequently validated through experimental tests. The results demonstrate a significant reduction in stator current total harmonic distortion (THD) and a noticeable decrease in torque ripple when compared with conventional SVPWM approaches.

Conclusions: By actively suppressing voltage components in the x–y subspace while preserving the desired voltage synthesis in the α–β plane, the proposed SVPWM strategy improves current quality and torque smoothness in six-phase induction machines. These features make the approach suitable for high-performance and high-reliability multiphase drive applications.

4.2. Feasibility Assessment of IEC 61800-9-2-2023 Standard in Switched Reluctance Motor Drives

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Introduction: Global electricity demand has increased significantly in recent decades, driven primarily by the growth of industrial and commercial activities. Electric motor systems account for more than 53% of the world's electricity consumption, with a strong predominance of the industrial sector. Despite the widespread use of three-phase induction motors, limitations such as reduced performance under partial loads, absence of direct speed control, high starting currents, and construction constraints have encouraged the search for technological alternatives. Regulatory requirements for energy efficiency, namely IEC 61800-9-2:2023, reinforce this need. In this context, SRM stands out as a promising solution, offering high power density and less dependence on critical materials. Thus, this work aims to analyze the energy performance of a switched reluctance motor and evaluate the applicability of the methods defined in IEC 61800-9-2:2023.

Methods: In this work, an experimental study was carried out on an SRM motor driven by a TURNtide converter. The losses of the motor, the Complete Drive Module (CDM) and the Power Drive System (PDS) are measured for two test methods: the method based on the IEC 61800-9-2:2023 standard, and a test method based on thermal stabilization. The motor drive is tested at the standardized operating points defined in the IEC 61800-9-2:2023 standard.

Results: The results indicate that the highest percentual variations occur in conditions far from the nominal regime, especially at low load torque and low speed, while the agreement between the methods is high at the operating points close to the nominal load.

Conclusion: The results indicate that the test method defined in IEC 61800-9-2 provides consistent loss estimations under nominal regimes but has limitations under partial load conditions. It is recommended to (i) integrate thermal stabilization at the standardized points and (ii) adapt the standard to the specificities of switched reluctance motor drives.

4.3. Impact of Power-Sharing Capability to Inter-Turn Short Circuits in Multiphase Synchronous Drives

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This article presents an advanced modeling framework for inter-turn short circuits (ITSCs) in segmented permanent magnet synchronous machines (PMSMs), with a focus on highly coupled segmentation (HCS) and multisector segmentation (MSS) winding architectures. As electric traction systems increasingly demand compactness and reliability—especially in aeronautics, electric vehicles, and renewable energy—ITSCs remain a critical failure mode, often leading to severe short-circuit currents and potential system collapse. While multiphase systems enhance fault tolerance for open-circuit faults, ITSCs pose unique challenges due to their propensity to propagate within motor windings. The study introduces a model that systematically analyzes ITSC faults in PMSMs operating under power-sharing conditions. Validated through experimental data from a dedicated laboratory test bench, the model demonstrates a strong alignment with real-world observations. A key innovation is the decoupling of intrinsic motor behavior (e.g., torque production and magnetic flux control) from the impact of power-sharing strategies, revealing how short-circuit currents are influenced by both resistive and inductive terms highly dependent on the segmentation technology. Comparative analysis highlights that MSS configurations exhibit greater sensitivity to power-sharing variations than HCS. This sensitivity stems from disparities in magnetic coupling: minimal in HCS but pronounced in MSS, where differential inductances significantly affect short-circuit currents. The findings underscore that while HCS maintains stability under power-sharing adjustments, MSS requires careful control to mitigate fault propagation risks. The model's predictive capabilities—spanning speed, short-circuit resistance, and differential current variations—provide actionable insights for designing fault-tolerant, power-sharing-capable drives. This work advances the understanding of ITSC dynamics in segmented PMSMs, offering a robust foundation for optimizing motor resilience in high-reliability applications.

4.4. A Direct Performance Comparison of Double-Stator Single-Rotor Axial-Flux and Inrunner Radial-Flux BLDC Motors at the 10 kW Power Level

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In this study, two Brushless Direct Current (BLDC) motor topologies—a dual-stator single-rotor axial-flux (DSSR-AF) BLDC motor and a radial-flux inner-rotor (RF inrunner) BLDC motor—are comparatively investigated under identical rated power (10 kW) and equivalent electrical and magnetic material properties. The two motor topologies are designed with distinct magnetic flux paths and structural architectures. The axial-flux motor employs an axial-flux path combined with a dual-stator configuration, whereas the radial-lux motor is based on a conventional inner-rotor structure with a radial-flux path.

During the preliminary design stage, analytical sizing methods are utilized, while the final electromagnetic performance evaluations are conducted using ANSYS RMxprt-assisted modeling and transient finite element analysis (FEA) performed in ANSYS Maxwell 2D. The comparative assessment includes key electromagnetic performance metrics such as average torque, torque ripple, magnetic flux density, efficiency, copper and iron losses, total losses, and torque and power density.

The simulation results indicate that the RF-BLDC motor achieves an efficiency approximately 4.71% higher than that of the DSSR-AF-BLDC motor. The average torque values are 24.6 Nm for the RF-BLDC motor and 13.7 Nm for the DSSR-AF-BLDC motor. The maximum air-gap magnetic flux densities are observed to be 0.48 T and 0.69 T, respectively. These findings demonstrate that the DSSR-AF-BLDC motor offers superior performance in terms of power and torque density, whereas the RF-BLDC motor exhibits an advantage in efficiency.

Although comparative studies on axial- and radial-flux BLDC motor topologies exist in the literature, direct comparisons of DSSR-AF-BLDC motors and conventional RF inrunner BLDC motors at the same power level under fully equivalent electromagnetic and material conditions remain limited. This study provides an original contribution by clearly revealing the efficiency–power density and torque-orientated performance trade-off for BLDC motor topology selection in electric unmanned aerial and ground vehicle applications at the 10 kW power level.

4.5. A Model-Based Online Current Optimisation of Sensorless Control of Synchronous Reluctance Machine Using Adaptive Full Order Observer (AFO)

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This paper proposes an online maximum torque per ampere (MTPA)-based current control and a modified speed estimation algorithm using a full-order speed observer for field-oriented control (FOC) of a synchronous reluctance motor (SynRM) traction drive for EVs. Unlike conventional MTPA methods based on offline look-up tables, the proposed approach computes the d-axis current reference online using a current-optimizing factor. The key concept is that the current-optimizing factor adapts automatically with operating conditions to keep the excitation level optimal: when load torque increases, the flux-producing component is increased to support torque production; however, during transient events, the current-optimizing factor decreases automatically, which limits the rise in flux and current and prevents over-excitation. At low speed or light load, the current-optimizing factor maintains an optimal stator current, reducing losses and improving overall efficiency. Quantitatively, although the conventional method also maintains the operating point, the proposed optimization reduces the flux from about 1.00 pu to about 0.85 pu at nearly nominal load (0.9 pu), while improving the power factor from about 0.45 to 0.65 at low load (0.2 pu) and from about 0.75 to 0.87 at high load (0.9 pu) in both motoring and regenerative modes. Additionally, to improve the robustness of speed estimation, the full-order observer is augmented with an explicit stabilization function. The stabilization function is obtained from the dot product of stator current and flux and is used to minimize oscillations and instability during low-speed motoring and regenerative modes, including under parameter variations and transients. The proposed speed estimator is evaluated by comparing the estimated speed with the motor speed across several EV driving profiles, including motoring, constant-speed, low- and zero-speed, and regenerative modes. The results show stable operation under load–torque disturbances and accurate speed tracking across the tested profiles, demonstrating that the proposed online current-optimizing MTPA strategy and stabilization-function-enhanced full-order observer are effective for sensorless SynRM traction control.

4.6. Comparative Analysis of LSTM, ANN, and KNN Architectures for Fault Detection and Diagnosis in Permanent Magnet DC Motors

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The reliability of Direct Current (DC) motors is critical to industrial productivity, yet mechanical components such as commutators and brushes are highly susceptible to wear and failure. This paper presents a rigorous comparative analysis of machine learning-based Fault Detection and Diagnosis (FDD) frameworks for Permanent Magnet DC (PMDC) motors. Specifically, we evaluate and compare the diagnostic performance of K-Nearest Neighbors (KNNs), Artificial Neural Networks (ANNs), and Long Short-Term Memory (LSTM) networks in classifying three operational states: Normal, Brush-Wear, and Commutator-Fault. Utilizing an open-source industrial dataset, each model was optimized to distinguish between subtle fault signatures that often lead to unplanned downtime. Our experimental results demonstrate a clear performance hierarchy: the baseline KNN model achieved an accuracy of 93.3% but was vulnerable to overlapping feature spaces, whereas the ANN improved accuracy to 94.7% by capturing non-linear relationships. The proposed

LSTM architecture significantly outperformed both models, achieving a superior validation accuracy of 97.4% and near-perfect precision for normal and brush-wear conditions. This superior performance is attributed to the LSTM's specialized gating mechanisms, which effectively capture long-term temporal dependencies within motor current and vibration signals. The study concludes that temporal deep learning models offer the most robust solution for automated predictive maintenance in complex industrial environments.

4.7. Comparative Analysis of Quad-Shaped Planar Coil Variants in a Stator Coreless Generator

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Recent advancements in electromagnetic machine design have driven significant interest in coreless topologies employing planar coils, owing to their lightweight structure and manufacturing advantages. This study presents a comparative analysis of four planar coil variants integrated into a Dual-Rotor Single-Stator Generator (SSDR), aiming to evaluate and enhance electromagnetic performance. The investigated coil geometries include Planar Square Coil (PSC), Planar Rhomboidal Coil (PRHC), Planar Trapezoidal Coil (PTC), and Planar Rectangular Coil (PRC). Finite element analysis (FEA) was employed to assess critical performance metrics such as coil flux density, magnetic field distribution, and flux linkage for each configuration. The results indicate that the PTC demonstrates superior electromagnetic characteristics, exhibiting an optimal flux distribution profile and high flux linkage. Among all tested variants, the PTC outperformed the PSC, PRHC, and PRC by 2.5%, 2.2%, and 1.75%, respectively, in overall electromagnetic performance. The PRC followed closely behind in terms of flux linkage but showed relatively less uniform field distribution. This comparative study underscores the potential of the trapezoidal planar coil for use in lightweight, high-efficiency SSDR generators. The findings provide valuable insights for optimizing planar winding designs in next-generation coreless generator applications. Future work will focus on experimental validation and thermal performance analysis of the proposed configurations.

4.8. Design and Analysis of a 45-Level Multilevel Inverter with Reduced Switch Count and Lower Voltage Stress

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Multilevel inverters have recently emerged as one of the promising approaches to DC–AC conversion in several medium- and high-voltage, high-power applications. These converters can generate the output voltage by synthesizing multiple discrete levels and offer superior waveform characteristics, such as lower harmonic content, better power quality, and lower electromagnetic interference compared to conventional two-level inverter systems. Nevertheless, most of the multilevel inverter topologies proposed so far require a large number of power semiconductor switches and other associated components, thus resulting in increased circuit complexity, higher implementation cost, and elevated switching losses.

In order to overcome said limitations, this work proposes a novel topology of multilevel inverter for obtaining staircase-shaped output voltages using a minimal count of switching devices. This proposed configuration makes use of six isolated DC voltage sources along with sixteen power switches, effectively providing a forty-five-level output voltage across the load. Even with reduced switch count, this inverter provides a finely stepped output voltage with increased resolution for better output waveform quality. Another important advantage of the proposed topology is the reduction in voltage stress suffered by the semiconductor devices. The lower voltage stress improves the reliability of an inverter to a great extent and also helps to choose lower voltage-rated switches, which in turn contributes to cost and efficiency improvement. A detailed comparison is carried out on the proposed topology considering component requirement, obtainable output voltage levels, and the distribution of voltage stresses among the switches. The performance of the proposed inverter is validated by detailed simulation studies. All the simulation results show stable and reliable operations under a wide range of loading conditions, includingboth linear and nonlinear loads. These findings prove that the proposed multilevel inverter topology is quite suitable for practical implementation in medium- and high-power conversion systems.

4.9. Experimental Evaluation of the IEC 61800-9-2:2023 Standard Applied to Advanced Variable-Speed Drive Systems Based on PMa-SynRM

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Introduction: Electric motors account for approximately 65% of global industrial electricity consumption, mainly due to oversizing and the use of inefficient flow-control methods.

To address this issue, the adoption of high-efficiency electric motors and the widespread adoption of variable frequency drives (VFDs) have emerged as key strategies for energy savings. However, the successful implementation of these technologies depends not only on technological innovation but also on the availability of robust standardized evaluation and classification procedures.

The International Electrotechnical Commission (IEC) introduced the IEC 61800-9-2:2023 standard, which defines testing procedures and classification systems for variable-speed electric drives. Nevertheless, its suitability for advanced variable-speed electric drives, such as Permanent Magnet-assisted Synchronous Reluctance Motors (PMa-SynRM) systems, operating under realistic industrial load profiles and harsh industrial conditions remains insufficiently validated.

Methods: In this work, an experimental study was conducted on a commercial PMa-SynRM driven by a Yaskawa A1000 VFD, comparing system losses obtained using the IEC 61800-9-2:2023 test procedure against an alternative method based on thermal stabilization at the eight standardized operating points.

Results: The comparison revealed consistent discrepancies between the IEC-based approach and the thermal stabilization method, with the largest deviations occurring away from rated conditions. These findings have relevant implications for the comparison of different power drive system (PDS) technologies.

Conclusion: For PMa-SynRM operated with Yaskawa A1000, the IEC 61800-9-2:2023 procedure leads to inaccurate loss measurements under practical load conditions. Therefore, the following recommendations are proposed: (i) consider thermal stabilization for the eight standardized operating points, and (ii) avoid misinterpretation and improve the technical suitability of IEC 61800-9-2, developing separate IEC standards, one for induction motors and another for synchronous motors.

4.10. Memory-Efficient AI Model for Virtual Voltage Vectors on Low-Cost Controllers in Asymmetrical Six-Phase Induction Machine Drives

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Introduction: Asymmetrical six-phase induction machines (A6PIM) inherently excite the secondary x–y subspace, producing circulating currents that do not contribute to torque, degrade current quality, and increase losses. In recent years, virtual voltage vector (VVV) modulation has been adopted to generate variable duty-cycle switching patterns; however, under fixed switching frequency operation, it typically relies on high-dimensional lookup tables (LUTs) to map the reference voltage (Vref, θref) into duty cycles. Although effective, this approach becomes impractical for low-cost processors due to excessive memory. This work addresses that bottleneck by replacing the LUT with an AI model that reproduces the original LUT duty cycles, thereby preserving the model behavior.

Methods: A sector-based VVV formulation is adopted in the α–β plane (24 sectors, 15° each). For each sector, a fixed set of active vectors is used with a symmetric pulse mid-sequence, and duty cycles are computed to match the α–β reference while enforcing zero average x–y voltage (and thus eliminating x–y current injection). An offline dataset is generated over the operating framework in (Vref, θref), and a compact regression model is trained to approximate the duty-cycle map (Vref, θref)↦{dk}. The resulting model is exported in a lightweight format suitable for DSP implementation.

Results: The AI model reproduces the LUT duty-cycle outputs with a very small error, while reducing memory requirements from approximately 175 MB to about 39 kB. Since the duty cycles (and corresponding switching commands) are replicated, the control VVV switching pattern and switching frequency are preserved. Real-time feasibility is compatible with low-cost control hardware such as the TMS320F28379D.

Conclusions: The main contribution is a memory-efficient AI model that replaces the VVV duty-cycle LUT while reproducing the original duty cycles, preserving the control modulation structure and switching frequency, and enabling real-time implementation on low-cost controllers for A6PIM.

4.11. *Overlap-Time Compensation in WBG-Based Current Source Inverters*

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Current source inverters (CSIs) represent an attractive alternative to conventional voltage source inverters in high-frequency applications, owing to their reduced output voltage stress and inherent short-circuit protection. However, the mandatory insertion of overlap time between switching states, required to guarantee a continuous current path for the DC-link inductor, introduces non-linear distortions into the synthesized output currents. These distortions strongly depend on the adopted space vector modulation (SVM) strategy and can significantly degrade the power quality and efficiency of the conversion system.

This paper presents an overlap time compensation methodology applicable to a wide range of carrier-based SVM strategies for CSIs. A unified classification framework is first introduced to uniquely identify switching patterns based on the number of segments and dwell time sequences. Building on this representation, the overlap time effects are analytically characterized by linking dwell time variations to the instantaneous phase voltage relationships. The proposed compensation algorithm performs an online correction of the dwell times, restoring the ideal reference current vector independently of the selected SVM pattern.

The effectiveness of the proposed approach is validated through comprehensive simulation and experimental investigations conducted on an induction motor drive. The conversion system was implemented with a DC–DC converter pre-stage supplying the CSI. The motor test bench consisted of an induction motor mechanically coupled to a DC motor, where the former controlled the torque and the latter regulated the speed. The results demonstrate a substantial reduction in low-order harmonic distortion in both output currents and voltages, with THD reductions of up to 90% for certain modulation strategies. Furthermore, the effective amplitude modulation index is recovered, achieving the required output current level, and the overall conversion efficiency improves, with measured gains of up to two percentage points.

4.12. Power Density Comparison of Flux-Modulating Machines for Wind Turbines

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Flux-modulating machines are emerging as noteworthy machines, particularly in wind turbines. They typically have two windings on their stators, which are not directly coupled, but use a flux-modulating rotor to cross-couple the two stator windings. These brushless machines are typically medium-speed machines, and they boast reliability suitable for remote areas with low accessibility.

Two popular machines in this category are the brushless doubly fed machines (BDFMs) and wound field flux switching machines (WFFSMs). Although these machines work according to similar operating principles, they have almost contrasting descriptions. BDFMs, viewed as alternatives to doubly fed induction generators (DFIGs), are noted for their comparably lower power density and efficiency. Conversely, WFFSMs are typically touted for their high power densities, hence the suggestions of replacing PM machines.

In this paper, the performances of BDFMs and WFFSMs are compared. Select topologies that operate at the same speed are evaluated: the 4/6 BDFM and the 24/10 WFFSM. Instead of applying a direct comparison between these two topologies, optimized 250 kW designs are compared to their conventional parallel topology. BDFMs are compared with DFIGs, while WFFSMs are compared with wound field synchronous machines. The optimization processes are conducted using the non-dominated sorting genetic algorithm coupled with response surface approximations from FEA evaluated designs.

It is shown that a 4/6, 250 kW BDFM typically has about 5% less efficiency compared to a 20-pole DFIG, while being almost two times the volume. The efficiency in WFFSMs is better due to less copper loss; however, their power factors are low. This is due to the cross-coupling nature of operations in BDFMs and WFFSMs, which leads to significantly lower flux utilization compared to their directly coupled counterparts. However, their reliability advantages cannot be dismissed.

4.13. Sensitivity Analysis-Based Multi-Objective Optimization of an Interior PMSM for Off-Highway Vehicles

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This paper presents a duty-cycle-driven design and optimization methodology for an Interior Permanent Magnet Synchronous Motor (IPMSM) intended for off-highway vehicle applications, based on real-world maneuver analysis. Off-highway machines such as wheel loaders operate under highly dynamic and repetitive load conditions that significantly differ from standardized road vehicle drive cycles. To accurately capture these operating characteristics, representative wheel-loader duty cycles are analyzed to extract realistic torque–speed–time operating envelopes. These envelopes are subsequently used to define application-specific performance targets and constraints, ensuring proper motor sizing and electromagnetic design aligned with real operating conditions.

A preliminary IPMSM design is first established using analytical sizing rules and electromagnetic design guidelines. This baseline design is then validated through high-fidelity finite-element analysis (FEA) using ANSYS Motor-CAD, enabling detailed evaluation of electromagnetic performance, losses, and efficiency under both steady-state and transient conditions. To systematically improve the motor design, a sensitivity analysis based on Design of Experiments (DoE) is conducted using ANSYS optiSLang. This step identifies the most influential geometric and magnetic design parameters affecting key performance indicators such as torque capability, efficiency, torque ripple, cogging torque, and motor mass.

Building on the sensitivity analysis results, a surrogate-assisted multi-objective optimization employing Particle Swarm Optimization (PSO) is performed. The optimization aims to enhance efficiency, reduce torque ripple and cogging torque, and minimize motor mass while satisfying strict electromagnetic, mechanical, and application-driven constraints. Comparative electromagnetic evaluation between preliminary and optimized designs demonstrates significant improvements in torque smoothness, harmonic content, and efficiency, confirming the effectiveness of the proposed optimization framework for off-highway electric powertrain applications.

5. Electromechanical Energy Conversion Systems

Comparative Performance Analysis of Spur and Chevron Gears in Wind Turbine Applications

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Wind energy is regarded as a critical point within the global energy market, especially for those countries that depend on this source to produce electrical energy. The efficiency of wind energy is, to a large extent, dependent on the efficiency of the transmission system parts, such as the gear. In wind energy, the gear is involved in the transmission of mechanical energy from the rotor to the generator. The intention of this study is to assess and compare the performance of spur and chevron gears in wind turbines, to fill the gap regarding the difference between theoretical and experimental efficiency related to high-speed winds. The study was based on comparisons of the performance between the theoretical and experimental results, and the results reveal that the difference between the theoretical and experimental performances for the spur gears was very low (less than 0.1%), indicating the accuracy of the theoretical models and their applicability to high-speed performance. Furthermore, the results indicated a significant discrepancy (up to 0.46%) for the chevron gears, related to certain elements not considered in the theory, such as lateral friction. In conclusion, this study demonstrated that spur gears are more reliable in predicting efficiency while calling for the development of more comprehensive theoretical models for chevron gears.

6. Mechatronics/Electromechatronics

6.1. A MATLAB Framework for Control and Experimental Research in Quadruped Robots

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Quadruped robots are increasingly used as experimental platforms for studying locomotion and control strategies in robotics. However, developing and validating control approaches often requires low-level programming and fragmented vendor tooling, which can hinder rapid experimentation and reduce repeatability. This work presents a MATLAB-based framework that enables systematic experimentation on a physical quadruped robot through a wireless communication layer while leveraging the robot's existing onboard motion stack. Instead of implementing gaits from scratch, the framework provides MATLAB-side access to baseline locomotion primitives already available on the platform (e.g., forward, stop, and turning commands), enabling the controlled experimentation and parameterized testing of locomotion and actuation behaviors, and complements them with low-level actuator access for controlled posture and joint/servo-level tests under conservative bounds and safety-oriented rate limiting. On the sensing side, the framework consolidates sensor feedback streams for experimental observation and logging, including actuator state and onboard sensing data used during experiments, depending on the available hardware configuration. The result is a simple closed-loop workflow in which MATLAB issues commands, the robot executes them using existing motion routines, and MATLAB captures synchronized feedback for repeatable trials and dataset generation. Experimental feasibility is demonstrated through experiments on a physical quadruped robot, including locomotion and posture command execution with real-time monitoring. The proposed framework lowers the barrier to structured experimentation and provides a practical foundation for future extensions, including adaptive control and learning-based methods for legged robots.

6.2. Characterization of Deformation and Pressure Fields in SpiRob Soft Grippers for Delicate Manipulation

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The safe and reliable manipulation of fragile objects remains a central challenge in soft robotics, particularly for cable-driven grippers in which actuation forces are indirectly transmitted through highly compliant structures. For automation and control purposes, establishing a link between the actuation variable—cable tension—and a physically meaningful grasp metric, such as contact pressure, is essential for defining operational safety limits. This work investigates the mechanical behaviour of a SpiRob-type soft gripper, with a specific focus on the characterization of contact pressure distribution under actuation. Rather than relying exclusively on detailed material calibration, this study explores modelling frameworks aimed at estimating the pressure generated at the gripper–object interface. The proposed approach analyses the structural response of the soft actuator to relate applied cable tension to the resulting contact pressure for objects with different geometries. Both theoretical and computational perspectives are employed to establish a robust mapping between actuation input and grasping performance. The resulting characterization enables the definition of pressure-based safety regions that are directly relevant to gripper design and low-level control strategies. By providing a practical method for estimating contact stress without the need for extensive experimental calibration, this work contributes to the development of safer, more predictable, and more controllable cable-driven soft robotic manipulation systems.

6.3. Reduction in the Driving Force in Bottom-Driven Scissor Lifts

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Introduction. Pantograph mechanisms are the most widely used parallel kinematic mechanisms. Their advantages include a single-drive architecture, high dynamic performance, and high positioning accuracy. The application of pantograph mechanisms is increasingly expanding in mobile robotic platforms and scissor lifts. Nevertheless, these mechanisms exhibit complex dynamic behavior and require sophisticated analytical and numerical approaches. Consequently, their analysis and modeling, especially considering energy-efficiency requirements, constitute an important practical research problem.

Methods. General methods of static and kinematic analysis were employed in this study. A calculation scheme was formulated, and analytical expressions were derived along with graphical representations of the support reactions, actuator force (driving force), and additional elastic forces as functions of the lever rotation angle.

Results. The scissor lift design additionally incorporates upper and lower extension and compression springs to unload the actuator implemented as a sliding screw–nut transmission. The stiffness coefficients of the additional springs were determined, and their operating conditions were taken into account. In the lower position of the pantograph mechanism, the upper spring is maximally extended; therefore, its force reaches a maximum value. During lifting, this force gradually decreases and becomes zero in the upper position of the platform. The lower spring is maximally compressed in the lower position of the platform and extends during platform lifting and lever rotation up to an angle of $\alpha = 25°$. Consequently, the influence of the lower spring on the levers is limited, whereas its elastic force magnitude exceeds that of the upper spring. The incorporation of these springs results in a 55.2% reduction in actuator force and a 59.4% reduction in internal forces compared to the configuration without springs.

Conclusions. The incorporation of additional springs into the pantograph lifting mechanism design is justified as an effective approach to reducing the actuator force and the reactions in the supports and joints.

6.4. Adaptive Shield Mechanism for UAVs Ensuring Reliable Structural Performance During Thermal Monitoring of Heritage Sites

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This work introduces an enhanced reconfigurable shielding mechanism for a novel drone, especially for cultural heritage monitoring, with a particular focus on thermal inspection of heritage buildings using an onboard thermal camera. The proposed mechanism allows for geometric transformation into compliant landing supports during landing operations and reconfiguration into a compact protective enclosure during flight. Experimental investigations identified misalignment problems in which the shield segments did not consistently return to their fully closed configuration. To overcome this limitation, a magnetic locking mechanism was developed by embedding permanent magnetic elements into designated structural sections, thereby ensuring accurate alignment and reliable mechanical locking in flight mode. To ensure reliable performance, the magnetic locking mechanism must provide adequate attractive force to withstand both vibrational disturbances and aerodynamic loads during dynamic flight conditions. Experimental validation confirms that the proposed design achieves substantial improvements in alignment accuracy and mechanical reliability relative to the baseline configuration. Furthermore, the redesigned structure establishes a protective zone around the propellers, thereby enhancing operational safety in confined cultural heritage environments. The magnetic-locking reconfigurable UAV protection system is effective at dealing with the problem of segment misalignment, providing greater resistance to the structure, and protecting the propulsion units during the flight. The experimental results prove that the system provides greater mechanical efficiency and reliability to ensure accurate acquisition of status data for a heritage site.

6.5. An Intelligent Automated Barrier for Mitigating Internal Flood Damage in Residential Buildings

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Introduction: Severe weather events such as floods are increasing in frequency and pose significant risks to homes, infrastructure, and human safety. Traditional domestic flood protection systems often require manual setup or user intervention, limiting their effectiveness during sudden flood events. Addressing this gap, we propose an integrated automated barrier system that is designed to reduce internal flooding and associated damage for residences located on sloped streets.

Methods: The developed system combines mechanical components with sensor-driven automation to detect rising floodwater and react in real time. The key elements include an array of hinged diverting plates (lintels) and a vertical sealing barrier installed at the entrance threshold. When sensors register imminent water ingress, the system autonomously deploys the lintels to redirect surface flow away from the doorway, creating a localized dry area. Simultaneously, the sealing barrier engages to prevent water from penetrating the the building's interior. The design process incorporated standard door dimensions and complied with relevant safety and automation regulations.

Results: Prototype testing under simulated flood conditions demonstrated consistent activation without human intervention, effective water diversion away from the entryway, and reduced internal water penetration compared to conventional static barriers. The automated control logic reliably interpreted sensor inputs, triggering timely deployment and retraction of barrier elements.

Conclusions: The intelligent automated barrier shows promise as a proactive residential flood mitigation solution that enhances response times and protects property with minimal human input. Future work will refine sensor calibration and assess long-term field performance across diverse flood scenarios.

6.6. Current Status and Implications of Artificial Intelligence Applications in the Ceramics Field from the Patent Perspective

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With the accelerated global intelligent transformation of the manufacturing industry, artificial intelligence (AI) technology has exhibited enormous application value in the ceramic industry. In particular, the integration of AI with robotics and mechatronics has become a key driving force for its intelligent production lines, automated processing, and real-time quality inspection. To explore current development and typical applications of AI in the ceramics field, especially its integration with robotics and mechatronic systems, this study retrieved 3773 patents from 2014 to 2024 via the IncoPat database, and adopted a combination of quantitative statistics and trend identification to analyze their development trends, legal statuses, applicant structures, technical characteristics, application scopes, and research hotspots. The results show that the annual patent applications present an overall upward trend, with China accounting for 84%. Valid patents account for 53.30%, while a high proportion of lapsed and withdrawn patents indicates that commercialization and maintenance costs remain key bottlenecks. Universities and local equipment manufacturers constitute the main applicants; the technical layout is concentrated in high-end intelligent equipment, mechatronic systems, robotic production lines, quality inspection and material optimization, with IPC classifications concentrated in G01N, G06N and B28B. AI has been applied throughout the ceramic production process, supported by robotics and mechatronics for automated execution, with research hotspots focusing on intelligent manufacturing and production automation, ceramic material optimization and performance prediction, as well as quality control and intelligent detection technologies. This study concludes that China has obvious advantages in the patent layout of AI applications in the ceramics field, but faces problems such as insufficient commercialization of high-value patents, low data sharing and lagging patent examination systems. It is suggested that the ceramic industry should strengthen the international patent layout, unify data standards, improve the patent examination system, and carry out interdisciplinary research combining AI, robotics and mechatronics to break through technical gaps.

6.7. Design Improvements and Experimental Characterization of a Sensored Rotating Crank for Arm Exercise

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Upper extremity injuries caused by trauma and repetitive movements are common among elderly individuals, manual labor workers, and athletes. A traditional rehabilitation program to restore range of motion and strength consists of massage, physiotherapy, and mechanotherapy. Although a great variety of commercial devices is available, the majority lack sensorization for performance monitoring. This paper presents a sensor-integrated rotating crank mechanism for upper limb rehabilitation by comparing the performance of three motor configurations and by validating the system's capability through quantitative motion parameters during exercise. Three prototype configurations were developed and tested. The first prototype (V0) was tested in passive mode without motor activation, then the stepper motor in (V1) was activated, and testing was carried out in semi-active mode. The third prototype (V3) was designed and tested in motorized mode. A 6-axis IMU sensor was integrated onto the crank to capture acceleration and orientation data. Testing was conducted with six volunteers (3 male, 3 female, aged 21–26 years) performing exercises in both horizontal and sagittal planes. The V0 configuration demonstrated predictable motion patterns with an acceleration magnitude ranging from approximately 9 to 13 m/s^2. Sagittal plane rotation exhibited higher variability with the range 5–20 m/s^2 due to gravitational effects. The V2 configuration introduced vibration and irregularities in motion smoothness with a magnitude acceleration range of 12 to 13.5 m/s^2. The most consistent performance was demonstrated by the brushless DC motor system (V3) with stable acceleration profiles (7–18 m/s^2 horizontal, 4–20 m/s^2 vertical). Acquired data revealed gender-related differences in peak acceleration, where male volunteers exhibited higher acceleration peaks, especially in the sagittal plane, where the Az component reached up to 25 m/s^2, whereas female volunteers showed lower and smoother acceleration profiles. The sensor-integrated system provided a reliable method for acquiring quantitative performance metrics, establishing a viable foundation for monitoring rehabilitation progress.

6.8. Development of a Low-Cost Hexapod Robot Mobility Aid for People with Visual Impairment

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This work presents a hexapod assistant robot that is designed to enhance the autonomy of people with visual impairment. Our primary objective was to create a modular, accessible, and low-cost robotic platform that serves as a technological alternative to traditional guiding methods, removing economic barriers and expanding access to independent mobility through the use of digital manufacturing technologies.

The mechanical design was modeled in 3D and manufactured using additive manufacturing in PLA. The system consists of six limbs with three degrees of freedom each, driven by 18 MG996R servomotors. The control architecture employs two ESP32 microcontrollers communicating via the ESP-NOW wireless protocol, enabling interaction between the robot and an ergonomic control unit. Inverse kinematics algorithms were implemented for leg movement, alongside a tripod gait pattern to optimize stability. The system incorporates ultrasonic sensors for autonomous obstacle avoidance and a custom-designed PCB that ensures a stable power supply, preventing voltage drops and system resets.

Tests conducted in controlled environments demonstrated the robot's ability to navigate autonomously and avoid collisions. The power system design successfully mitigated voltage spikes, allowing for smooth and continuous operation during navigation trials.

The results validate the technical feasibility of the prototype as a mobility assistant. Despite limitations in leg traction or sensor precision, the design lays the foundation for future applications in personal guidance, as well as rescue tasks or industrial inspection in irregular terrains.

6.9. Development of a Robotic Module Coupled to a Drone for Installation of Spacers in High-Voltage Cables

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With industrial and residential electricity demands on the increase, electrification plays a fundamental role in providing the necessary infrastructure for this constant evolution, which fuels several sectors that are important to society. To distribute electricity on a large scale and over long distances, high-voltage transmission systems, which operate at very high voltages with multiple cables, are commonly used worldwide. These cables must be spaced apart to ensure that they do not come into contact. Thus, in this paper, we develop a robotic module coupled with a drone that is used to install spacers. Spacers are elements that are used between various cables within a power distribution system to keep them apart. The drone transports the robotic module to the cable, controls the robotic module using radio signals, and installs/uninstalls the spacer. After completing the procedure, the drone searches for the robotic module, returning it to the ground station to repeat the operation if necessary. This paper describes the development of the mathematical model followed by the CAD/CAE design. Computer simulations verified the feasibility of using this robotic module for installing spacers. It is noteworthy that this module can be placed on cables using a drone or a hot stick, eliminating the need for technicians to come into direct contact with the cables or to move along them. This drone–robot aims to reduce risks for technicians who carry out these operations by climbing the towers and moving on cables or in some cases may be suspended from a platform fixed to a helicopter.

6.10. Development of an Autonomous Electric Robotic System for Intra-Row Weeding

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Intra-row weeding is a time-consuming and technically demanding operation in orchard and vineyard management, requiring high precision to avoid damage to crop trunks while ensuring effective weed removal. To address this challenge, a rotary weeder implement integrated with an autonomous electric robot was developed and evaluated. The conventional hydraulic drive system was replaced with an electric motor, and selected mechanical components were redesigned to reduce the overall weight of the implement. Side-shift, height, and tilt adjustments were achieved using linear electric actuators to enable precise positioning during operation. For trunk detection, two sensing approaches were investigated, namely a conventional electromechanical feeler sensor and a sonar-based sensor. Autonomous row following was accomplished using data acquired from a two-dimensional laser scanner. The robotic prototype was experimentally evaluated at a forward speed of 0.16 m s^{-1} and a working depth of 40 mm. The overall performance of both trunk detection systems was assessed in terms of weeding quality and power consumption. The experimental results demonstrated that the autonomous intra-row weeding robot could serve as a viable alternative to conventional machinery. Among the tested sensing systems, the sonar sensor exhibited superior performance compared to the adjusted feeler mechanism. The integration of autonomous navigation with electric weeding technology showed potential to improve weeding quality while reducing power requirements in future field applications.

6.11. Dielectric and Structural Optimization of Silicon Carbide/Polystyrene Composites for Mechatronic Applications

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Silicon carbide/polystyrene composites with SiC contents of 1–10 wt% were developed to evaluate their potential as multifunctional materials for mechatronic and electromechatronic components, such as high-precision sensor substrates, dielectric layers for micro-actuators, and EMI-shielding elements. In such systems, materials with tunable permittivity and structural stability are essential in ensuring reliable signal conditioning and stable operation under alternating electromagnetic fields. Structural investigations by SEM and XRD confirmed that highly crystalline β-SiC particles (3–15 μm) are successfully dispersed within the amorphous PS matrix. Williamson–Hall analysis revealed that the 7 wt% composite exhibits the largest crystallite size (≈30.23 nm) and the lowest microstrain. This enhanced structural uniformity is critical in maintaining the mechanical integrity of mechatronic assemblies subjected to operational vibrations and thermal cycling. Dielectric spectroscopy showed a systematic increase in permittivity with SiC concentration, attributed to Maxwell–Wagner–Sillars interfacial polarization. This behavior is specifically analyzed in the context of electromechatronic interfaces, where controlled charge accumulation influences insulation performance and signal transmission stability. UV–Vis and FTIR analyses confirmed the chemical stability and improved structural uniformity of the composites. The results demonstrate that SiC/PS composites offer a tunable platform for advanced mechatronic applications, providing the necessary balance between dielectric performance and structural reliability for integrated robotic and electronic systems.

6.12. Intelligent Mechatronic Design of an Implantable Monitoring System Using Embedded AI

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The continuous monitoring of patients affected by Alzheimer's disease requires autonomous and reliable machine-based systems capable of operating under strict energy, size, and safety constraints. This work proposes an intelligent mechatronic architecture for an implantable monitoring device integrating embedded biomedical sensors, low-power processing units, secure wireless communication, and artificial intelligence for real-time data analysis. To address the limited availability of clinical datasets, a digital twin-based synthetic data generation framework is developed. The proposed system is evaluated on a multidimensional dataset composed of 10, 235 records, including physiological, behavioral, and cognitive parameters, with an 80/20 train-test split. Random Forest, Support Vector Machine, and Deep Neural Network models are implemented and compared using standardized classification and regression metrics, including accuracy, precision, recall, F1-score, confusion matrices, and error-based indicators. The experimental results show that the Deep Neural Network consistently outperforms classical machine learning models, achieving higher classification accuracy, reduced misclassification rates, and more stable convergence behavior, as confirmed by learning and loss curves. From a mechatronics perspective, the proposed solution emphasizes modular system integration, computational efficiency, and compatibility with implantable hardware constraints. The results demonstrate the feasibility of embedding intelligent decision-making capabilities into compact mechatronic systems, highlighting their relevance for intelligent machines and continuous monitoring applications.

6.13. Mechatronic System Design of a Low-Cost Near-Infrared Vein Visualization Platform Based on Optoelectronic Integration

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Near-infrared (NIR) imaging systems have demonstrated significant potential for enhancing subcutaneous visualization applications; however, existing solutions are typically based on proprietary architectures with limited accessibility for experimental and engineering development. This work presents the mechanical and mechatronic design of a low-cost NIR vein visualization platform focused on optoelectronic integration, structural stability, and real-time image acquisition performance. The proposed system combines a controlled NIR illumination module, an infrared-sensitive imaging unit, and a compact processing architecture designed to operate under constrained computational resources while maintaining consistent visualization conditions. The mechanical structure was developed to ensure fixed spatial alignment between illumination and sensing components, minimizing optical noise and shadow artifacts through controlled geometry and working distance optimization. Image processing routines based on grayscale conversion and contrast enhancement were implemented to improve signal differentiation between vascular and surrounding tissue structures while preserving real-time operation capability. The modular architecture enables rapid prototyping, component scalability, and reproducibility using commercially available hardware elements. Experimental functional evaluation demonstrated stable visualization of superficial vascular patterns under controlled conditions, confirming adequate optical response and system repeatability for continuous operation scenarios. Compared with commercially available systems, the proposed platform significantly reduces implementation cost while preserving essential functional performance required for optoelectronic sensing applications. The presented design highlights the potential of low-cost mechatronic integration for developing scalable optical sensing platforms, providing a foundation for future improvements involving automated calibration, advanced image processing, and adaptive control strategies in electromechatronic systems.

6.14. Modern Control System Architectures and Methods for Collaborative Manipulators

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Collaborative manipulators are often deployed as robotic systems that are intended to operate safely and intuitively within shared workspaces alongside human users. Their effectiveness depends not only on mechanical design, but also on the reliability of the underlying control architecture, the quality of sensor feedback, and the system's ability to adapt to human interaction in real time. This study provides a structured review of modern control strategies used in collaborative manipulators, examining the theoretical principles and practical implementation of impedance, admittance, hybrid, and sensor-based approaches. An analysis of the existing literature shows that impedance and admittance control techniques are particularly well suited for human–robot collaboration, as they help to maintain stability during contact while enabling compliant and responsive motion that aligns with human intent.

This paper introduces a conceptual multi-layer control architecture that integrates safety supervision, trajectory planning, and sensor fusion. Within this architecture, a hybrid control scheme that combines force and motion sensing is highlighted as a promising direction for achieving adaptive behavior. Such an approach supports real-time adjustment of dynamic parameters and aligns with the safety limits defined in ISO/TS 15066, ensuring controlled contact forces and safe motion near human operators.

Overall, the presented framework offers a comprehensive theoretical foundation for further development of adaptive and sensor-rich control systems. These insights are expected to contribute to subsequent simulation studies, prototype testing, and the broader implementation of collaborative robots in industrial, medical, and human-assistive applications.

6.15. Passive Joint Friction in Low-Cost Delta Parallel Robots: A Parametric Analysis Using Multibody Simulation

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Friction in passive joints plays a critical role in the dynamic behavior, accuracy, repeatability, and energetic efficiency of parallel robotic systems, particularly in Delta-type architectures. These effects are especially pronounced in low-cost robotic platforms, where manufacturing tolerances, material choices, and joint surface quality can significantly amplify friction-related phenomena. This paper presents a parametric analysis of joint friction effects on the dynamic and kinematic performance of a low-cost Delta parallel robot, based on an existing multibody model developed in the MATLAB Simscape Multibody environment. The proposed methodology exploits the native joint friction modeling capabilities of Simscape Multibody, enabling the systematic introduction and comparison of different friction formulations within the robot's passive joints. Several friction models are considered, ranging from classical Coulomb and viscous formulations to nonlinear models capable of capturing velocity-dependent effects. The influence of friction parameter variations is evaluated in terms of positioning accuracy, repeatability, dynamic response, and mechanical energy consumption along representative motion trajectories. Particular attention is given to the trade-off between increased energy demand due to friction and its stabilizing effect on the system's dynamic behavior. The results provide insight into how friction modeling choices and parameter values affect the overall performance of low-cost Delta robots, supporting informed decision-making during mechanical design and simulation-based analysis. The proposed framework also establishes a foundation for future extensions toward vibration analysis, wear modeling, and friction-aware control strategies.

6.16. Proposed Design of a Cube Cable-Driven Parallel Robot Design for Rehabilitation Exercises and Precision 3D Manufacturing

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This work addresses a novel design of a cable-driven parallel robot cube structure. The primary purpose of developing the new robotic structure, as described in this paper, was to integrate the capabilities and skills of 3D printer innovative technology by cable-driven robots and provide high-precision manufacturing by 3D printing capabilities for artistic work of different sizes. The proposed design is intended to operate in a three-dimensional workspace, with the possibility of incorporating more degrees of freedom depending on the specific application requirements. The Cube CDPR structure consists of a mobile platform that has the capability of moving dynamically along the vertical (Z-axis) with sliding movement. This configuration provides increased structural flexibility relative to the rigid and stable platforms typically employed in cable-driven parallel robot architectures. The Cube CDPR structure incorporates four independent motors positioned at the corner edges of the platform. Each motor drives a cable through a pulley system, and coordinated control of cable unwinding and rewinding enables precise regulation of the end-effector position and orientation. The four cables are actuated by stepper motors on the mobile platform, while a fifth control motor adjusts the base position along the Z-axis through vertical sliding motion. This integrated control strategy enables simultaneous control of the platform configuration and end-effector position. Smooth and stable motion is achieved through controlled motor actuation. The cable-driven architecture helps to minimize the mass in motion, while dexterity and resolution of the movements are maximized, which is a requirement for drawing and complex 3D printing. The proposed Cube structure and mechanical configuration are simulated and validated. The characteristics mentioned above show the potential of the proposed system in the fields of artistic robotics and 3D printing.

6.17. Reconciling Ingress Protection and Thermal Management in Sealed Motor Enclosures for Low-Cost Delta Robots

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Low-cost Delta robots manufactured using additive manufacturing technologies are becoming increasing prevalent in educational, research, and light industrial environments. Despite their advantages in terms of cost and flexibility, these systems are typically designed for clean indoor conditions and therefore have limited protection against dust, humidity and water splashes. In particular, the motor enclosure that houses the wiring and internal electronic components often exhibits a low Ingress Protection (IP) rating, restricting operation in harsher or semi-industrial environments.

Improving enclosure tightness to achieve higher IP levels, such as IP54, inevitably reduces natural ventilation and limits heat dissipation. This issue is especially critical because the internal electronic components dissipate residual heat of approximately 5 W, while the enclosure is predominantly made of plastic materials with low thermal conductivity. As a result, increased sealing may lead to elevated internal temperatures that compromise motor reliability, continuous operation, and long-term durability.

To address this trade-off, the present work focuses primarily on CFD-based thermal modelling to reconcile ingress protection with effective thermal management. The methodology includes mechanical redesign of the enclosure in 3D CAD, estimation of internal heat sources, and detailed CFD simulations using ANSYS Fluent, considering steady-state and transient conjugate heat transfer. Several enclosure configurations corresponding to different strategies for achieving equivalent IP ratings are analysed, and multiple thermal enhancement hypotheses—such as modifications to materials, geometry and heat-spreading features—are evaluated and quantitatively compared using CFD.

While the core of this work relies on detailed CFD modelling, simplified experimental measurements are performed to obtain indicative temperature levels and to support the interpretation of the numerical trends, rather than to provide full model validation.

The results aim to identify enclosure design solutions that maintain high IP tightness while ensuring acceptable operating temperatures, enabling the deployment of low-cost Delta robots in more demanding environments without compromising thermal safety or manufacturability.

6.18. Structural and Parametric Synthesis of Adaptive Locomotion Mechanisms for In-Pipe Robots Performing Internal Pipeline Surface Diagnostics

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Introduction. In-pipe robots enable non-destructive diagnostics of internal pipeline surfaces in water, oil-and-gas, and process industries, where access is limited and inspection conditions vary substantially. Reliable operation requires adaptive locomotion that maintains traction and stability across diameter changes, bends, joints, and deposits while providing predictable sensor standoff and scan coverage. This paper presents a structural and parametric synthesis approach for designing adaptive locomotion mechanisms for in-pipe robots intended for internal pipeline surface diagnostics.

Methods. A structural–parametric synthesis framework was developed to formalize the pipeline environment as a set of geometric and contact constraints (diameter range, curvature, obstacles, allowable normal forces), generate candidate locomotion structures (multi-module wheeled/tracked and clamping–propulsion hybrid concepts) with explicit compliance and reconfiguration elements, and perform parametric synthesis via constrained multi-objective optimization. Design variables include linkage geometry, module spacing, wheel/track radii, compliant element stiffness, and clamping preload. Objective functions minimize slip risk and energy demand while maximizing traversability (minimum negotiable bend radius and step height) and diagnostic quality indicators (sensor standoff stability and coverage uniformity). The models incorporate quasi-static contact mechanics with Coulomb friction and a simplified actuator capacity model.

Results. Our method produces Pareto-optimal designs that balance traversability, traction margin, and diagnostic stability. Synthesized mechanisms demonstrate improved passability of diameter transitions and elbows while maintaining bounded contact forces compatible with pipeline integrity constraints. Compared with baseline fixed-geometry concepts, adaptive designs yield higher traction margins, reduced sensitivity to friction variability, and more stable sensor standoff, which directly improves the repeatability of surface diagnostic measurements.

Conclusions. Structural and parametric synthesis provides a systematic route for designing adaptive in-pipe locomotion mechanisms tailored to specific pipeline networks and diagnostic tasks. The resulting design maps and Pareto sets support evidence-based mechanism selection and parameter tuning, improving mobility robustness and measurement quality for internal pipeline surface diagnostics.

6.19. Structural and Parametric Synthesis of Biomimetic Upper-Limb Exoskeleton Mechanisms for Motor Function Restoration

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Introduction. Upper-limb exoskeletons for rehabilitation and assistive therapy must reproduce anatomically plausible motions while ensuring kinematic compatibility with the human arm to reduce parasitic joint loads, discomfort, and misalignment. Achieving this requires a systematic synthesis of mechanism topology and geometric parameters under biomechanical constraints and device-level requirements. This paper addresses the structural and parametric synthesis of biomimetic upper-limb exoskeleton mechanisms aimed at restoring motor functions after neuromuscular impairment.

Methods. A structural and parametric design framework was developed that defines target human joint trajectories and ranges of motion for the shoulder–elbow–forearm chain, generates candidate mechanism structures (serial, parallel, and hybrid linkages with redundant/self-aligning degrees of freedom), and performs parametric synthesis via constrained optimization. The objective functions include kinematic alignment error (distance between anatomical and exoskeleton instantaneous axes/centers), workspace coverage, and isotropy-related metrics, while constraints enforce joint limits, link interference avoidance, and attachment ergonomics. The optimization uses multi-objective search with penalty handling to identify Pareto-optimal solutions and robustness to anthropometric variability.

Results. The proposed approach yields families of feasible exoskeleton mechanisms that match prescribed joint kinematics with reduced alignment error across the rehabilitation workspace. Compared with baseline designs, synthesized mechanisms demonstrate improved workspace consistency and lower sensitivity to user-specific limb dimensions while maintaining compact link lengths and acceptable joint conditioning. The obtained Pareto set highlights trade-offs between alignment accuracy, mechanism complexity, and ergonomic constraints, providing quantitative guidance for selecting structures tailored to specific therapeutic tasks.

Conclusions. Structural and parametric synthesis enables the principled development of biomimetic upper-limb exoskeleton mechanisms that better conform to human joint kinematics and anthropometric diversity. The resulting designs are expected to improve comfort and safety and to support more effective motor function restoration through enhanced human–robot kinematic compatibility.

6.20. System Identification Applied to the Dynamic Modeling of a Robotic Joint with Elastic Transmission

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Modern robotic systems require actuators capable of delivering high precision and reliable performance across diverse tasks. In this context, the BEAR (Belt Elastic Actuator for Robotics), developed by Smile.Tech, is a belt-driven elastic robotic actuator, conceived as an active joint suitable for multiple robotic architectures and applications. Its elastic transmission provides reduced mechanical backlash compared to traditional rigid-gear solutions, ensuring consistent motion. However, the BEAR is currently operated through trial-and-error using position feedback from two encoders—one on the motor and one on the output shaft—whereby performance depends on empirical tuning, reducing reliability in more dynamic operating regimes. This paper presents the identification of the BEAR actuator, producing models that describe its dynamic behaviour. These models make it possible to replace empirical tuning, enabling predictive simulation, supporting advanced control methods, and allowing systematic use of the actuator's elastic properties. The proposed study relies on dedicated experimental input–output data to characterise the dynamic behaviour of the BEAR actuator under relevant operating conditions. These data are used in grey-box modelling, combining the physical knowledge of the system and data-driven parameter estimation. Prior to application on the BEAR, the approach is validated on progressively complex systems, allowing refinement of the identification procedure and ensuring the reliability of the resulting models. This study aims to develop a consistent model of the BEAR actuator, establishing a quantitative foundation for subsequent analysis and control. By enabling model-based operation and control design, this work seeks to support improved precision, predictability, and reliability in robotic tasks, with potential implications for multifunctional elastic joint applications.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.