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Recent Trends in Energy-Efficient Design of Mechatronic Systems: A Comprehensive Review

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HIGHLIGHTS

- Takes a look at recent trends (2019–2025) in energy-saving mechatronic systems, exploring how they integrate elements like smart materials, AI, IoT, and renewable energy.
- Suggests a practical framework that brings together low-power electronics, advanced control techniques, and energy harvesting methods.
- Highlights real-world examples showing significant energy savings using technologies such as regenerative braking, AI-based control, and self-powered sensors.
- Pinpoints the main challenges today and outlines promising directions for future research in energy-efficient design.
- Offers side-by-side comparisons of different technologies, control strategies, and smart actuators, focusing on their trade-offs and readiness.

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ABSTRACT

The push for sustainability and energy efficiency is driving innovation in the design of modern mechatronic systems. This review examines key developments from 2019 to 2025 in reducing energy consumption across mechanical, electrical, and control components. It highlights practical strategies such as low-power electronics, efficient control algorithms (e.g., model predictive, adaptive control), and energy-harvesting techniques. This review explores how smart materials—such as piezoelectrics and shape memory alloys—can enhance the efficiency of actuators. It also examines emerging approaches like co-design optimization, digital twins, and predictive maintenance powered by AI, all of which aim to reduce energy consumption throughout a system's life. Through real-world case studies in robotics, automotive systems, and industrial automation, the paper highlights recurring design challenges and trade-offs. The review wraps up with key recommendations for future research, focusing on the development of smarter, more sustainable, and better-integrated mechatronic systems.

Keywords:
Artificial intelligence, energy efficiency, mechatronic systems, smart materials.

Notations

Symbol/Abbreviation	Definition
AI	Artificial Intelligence
IoT	Internet of Things
MPC	Model Predictive Control
SMA	Shape Memory Alloy
EAP	Electroactive Polymer
MEMS	Micro-Electro-Mechanical Systems
PWM	Pulse Width Modulation
SMC	Sliding Mode Control
ML	Machine Learning
DC	Direct Current
AC	Alternating Current
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
PLC	Programmable Logic Controller
DAQ	Data Acquisition
CPU	Central Processing Unit
GPU	Graphics Processing Unit
DSP	Digital Signal Processing
RF	Radio Frequency
LPF	Low Pass Filter
HPF	High Pass Filter
PID	oportional–Integral–Derivative (Control)
RMS	Root Mean Square
DOF	Degrees Of Freedom

I. INTRODUCTION

The global push closer to sustainability has made energy efficiency has become a key consideration in how modern-day mechatronic structures are designed and advanced. These systems—seamlessly combining mechanical, electrical, and control additives—are the riding force behind innovations like business robots, independent cars, and wise automation platforms [1], [2]. As industries are looking for out technologies that are not only excessive-acting however additionally environmentally responsible, electricity-conscious design has turn out to be extra crucial than ever [3].

Improving power performance in mechatronics isn't pretty much slicing energy intake—it additionally approach decreasing operational charges, managing warmth greater efficiently, and boosting long-term machine reliability. Engineers have made most important strides on this location, incorporating low-energy electronics, incorporated sensor-actuator networks, and smarter manipulate algorithms to streamline performance [4], [5]. Meanwhile, advanced materials like piezoelectric actuators and shape memory alloys are providing light-weight, responsive options to conventional components, substantially lowering energy use [6], [7].

On the manipulate side, techniques which include version predictive manage, fuzzy common sense, and AI-based totally algorithms are assisting to minimize electricity utilization even as still retaining precision and stability [8]–[10]. Tools like virtual twins and co-layout frameworks at the moment are being used proper from the early layout phase, making it less difficult to embed electricity optimization into every layer of system improvement [11], [12].

With mobile and stale-grid programs becoming extra not unusual, electricity harvesting technologies that faucet into ambient resources like vibration or solar power are gaining traction [13], [14]. At the identical time, using low-energy microcontrollers and energy-green conversation protocols is helping to shrink the general energy footprint of contemporary mechatronic structures [15], [16].

Recent developments additionally emphasize lifecycle electricity evaluation and predictive maintenance to make sure long-term sustainability and overall performance [17], [18]. As clever factories and robotics emerge as more common, power-efficient design have to scale to meet the demands of self sufficient and adaptive structures [19], [20].

Integrating synthetic intelligence (AI), the Internet of Things (IoT), and edge computing technology promises a destiny of clever, sustainable mechatronic systems [21]–[25].

This paper is driven by the urgent need to address rising energy demands, environmental concerns, and the lack of a unified framework for energy-efficient design across mechatronic disciplines. It aims to consolidate recent developments (2019–2025), explore cross-disciplinary approaches, and present a roadmap for future innovations that enhance energy efficiency at both component and system levels.

The motivation behind this work stems from the rapid advancement of automation, robotics, and intelligent systems, which has significantly increased global energy consumption—particularly through mechatronic systems that integrate mechanical, electrical, and control components. With heightened environmental concerns and tightening regulatory standards, the demand for sustainable, energy-efficient systems has become more pressing than ever. Mechatronic systems, being central to industries such as manufacturing, transportation, healthcare, and consumer electronics, offer a substantial opportunity for reducing energy usage. However, despite ongoing research, efforts remain fragmented across domains and lack a unified vision. This work brings together recent technological advancements to lay the groundwork for future innovations in designing energy-smart mechatronic systems.

Our main goal here is to offer a thorough review of the latest trends in energy-efficient mechatronic system design, specifically looking at developments between 2019 and 2025. We explore key advances in areas like smart materials, better actuators, low-power electronics, and control techniques that help boost energy performance. We also look at how combining tools like artificial intelligence, the Internet of Things (IoT), digital twins, and energy harvesting technologies can lead to more holistic energy optimization.

To make this practical, the paper examines real-world case studies and points towards promising directions for future research and development. Ultimately, we want to give researchers and engineers a solid, detailed understanding of how to create intelligent, autonomous, and sustainable mechatronic systems for the future. This review paper is systematically structured into eleven key sections, each addressing a specific dimension of energy-efficient mechatronic system design. In this section, the background and contextual motivation for pursuing energy efficiency in mechatronic systems are presented, highlighting the global push toward sustainability and the role of intelligent automation in reducing energy consumption. Section II, fundamentals of energy-efficient mechatronic design, introduces foundational concepts, key design considerations, and system-level energy modeling techniques essential for minimizing energy consumption while maintaining system performance. Section III, smart materials and actuators, explores the application of innovative materials—such as piezoelectrics, shape memory alloys, and electroactive polymers—that reduce actuator energy demands and enable lightweight, responsive designs. Section IV, integration of renewable energy in mechatronic systems, examines the utilization of solar, wind, and hybrid energy sources to support sustainable operations, particularly in autonomous and mobile systems. Section V, IoT and edge computing in energy-conscious mechatronics, focuses on smart connectivity, distributed processing, and real-time data analytics for decentralized and efficient energy management. Section VI, energy harvesting techniques, reviews methods for capturing ambient energy—such as kinetic, thermal, and vibrational energy—to power low-consumption components and extend system autonomy. Section VII, thermal management and waste energy utilization, addresses energy recycling and efficient heat dissipation strategies that improve system efficiency and longevity. Section VIII, case studies and industrial applications, presents real-world implementations and comparative analyses. Section IX, challenges and future directions, outlines current technical barriers-such as trade-offs between energy efficiency and performance—and highlights emerging research areas including lifecycle sustainability and co-design methodologies. Section X, conclusion, synthesizes key insights from the review, emphasizing strategic recommendations and advocating for interdisciplinary collaboration in advancing energy-efficient mechatronic systems.

II. FUNDAMENTALS OF ENERGY-EFFICIENT MECHATRONIC DESIGN

Manuscripts Energy-efficient mechatronic design is a multidisciplinary endeavor that integrates mechanical, electrical, and control components to minimize energy consumption while ensuring optimal system performance. At the heart of this approach lies the principle of design-for-efficiency, which emphasizes making energy-conscious decisions from the earliest design stages. This includes the selection of lightweight materials, low-friction components, high-efficiency actuators, and low-power electronics that contribute to minimizing overall energy demands [26], [27].

System-level energy modeling plays a crucial role in understanding and predicting energy behavior throughout a mechatronic system's lifecycle. Advanced simulation platforms allow designers to evaluate energy usage under varying conditions, helping identify inefficiencies and opportunities for optimization [28]. These tools support multi-objective optimization techniques that help balance energy efficiency with critical performance metrics such as response time, accuracy, and robustness [29], [30].

Control strategies are central to energy optimization efforts. Techniques such as model predictive control, adaptive control, and AI-based optimization dynamically adjust system operation in response to environmental changes and task demands, improving real-time energy efficiency [31], [32]. Table I summarizes energy-aware control strategies and their suitability for different system demands.

TABLE I. CONTROL STRATEGY VS. ENERGY OPTIMIZATION IMPACT [1], [4], [8–10], [30–32]

Control Strategy	Key Benefit	Energy Reduction Capability	Complexity	Best Fit Applications
Model Predictive Control	Anticipatory control via modeling	High	High	Autonomous vehicles, adaptive machines
Fuzzy Logic Control	Handles uncertainty, simple design	Moderate	Medium	HVAC, prosthetics, simple actuators
AI-based Optimization	Learns patterns, adaptive responses	Very High	High	Smart factories, predictive maintenance
Adaptive Control	Real-time parameter adjustment	Moderate	Medium	Robotics, varying load systems
PID Control (Optimized)	Widely used, easy to implement	Low to Moderate	Low	Conventional mechatronics

Meanwhile, the intelligent selection of actuators and sensors—especially those utilizing smart materials like shape memory alloys and piezo electrics—further supports energy savings by offering compact and responsive solutions with low energy requirements [33], [34].

Thermal management and energy recycling are increasingly recognized as vital components of efficient system design. Effective dissipation of waste heat, along with mechanisms for heat recovery, enhance system sustainability, particularly in high-power or continuous-duty applications [35]. Additionally, integrating renewable energy sources such as solar or kinetic harvesting into mobile or remote mechatronic platforms enables greater autonomy and reduces reliance on external power supplies [36], [37].

The incorporation of digital twins, predictive maintenance, and AI-driven forecasting tools extends energy optimization beyond the design phase into ongoing operation and system lifecycle management. These digital tools help monitor real-time energy usage, anticipate failures, and maintain high energy performance through continuous updates and adjustments [38].

Altogether, the fundamentals of electricity-green mechatronic design demand a holistic expertise of system behavior, thing interactions, and real-time adaptability. Through wise integration of design principles, advanced modeling, smart manage, and energy-aware technology, contemporary mechatronic structures can achieve both sustainability and excessive functionality. To better apprehend the combination of key additives involved in achieving energy efficiency in mechatronic systems, a structured design framework is critical. This framework captures the interrelated tiers of device layout, which include optimization of components, application of clever manage strategies, and non-stop electricity analysis. It highlights how power- efficient effects are finished thru a stability of hardware choices, software program algorithms, and remarks from actual-time performance metrics. *Fig. 1* illustrates this conceptual flow, guiding the systematic implementation of energy-saving strategies in modern mechatronic applications.

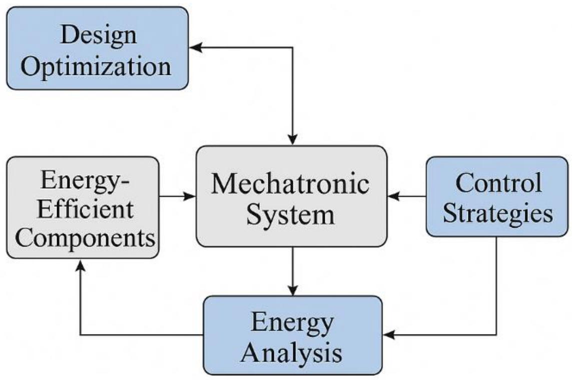

FIG.1. STRUCTURED FRAMEWORK FOR ENERGY-EFFICIENT MECHATRONIC SYSTEM DESIGN.

III. SMART MATERIALS AND ACTUATORS

Sustainability has emerged as a cornerstone of modern mechatronic layout. Innovations emphasize power-green answers, along with renewable energy integration, eco-friendly substances, and algorithms that decrease waste. For instance, solar-powered robots and AI-pushed maintenance structures are extending equipment lifespans whilst reducing environmental effect. These advancements underscore a broader commitment to balancing technological progress with ecological responsibility [39] [40].

Advances in smart materials and actuators are equally transformative. Electrically driven polymer-based flexible actuators, for example, are gaining prominence in soft robotics and wearable technologies due to their bioinspired designs and adaptability. Dielectric elastomer actuators offer high efficiency for lightweight, responsive mechanisms, while shape-memory polymers enable reversible actuation and self-sensing capabilities, expanding their utility in diverse applications [40], [41].

Table II outlines a comparative analysis of smart actuator types, focusing on their energy efficiency and relevant application domains within mechatronic systems.

TABLE II. COMPARISON OF SMART ACTUATOR TYPES VS. ENERGY CONSUMPTION AND EFFICIENCY [5–7], [14], [33], [40–42]

Actuator Type	Smart Material Used	Typical Energy Source	Energy Efficiency	Response Time	Application Domain
Piezoelectric Actuator	Piezoelectric Ceramics	Electrical (low V)	High	Fast (ms)	Precision robotics, medical tools
Shape Memory Alloy (SMA)	Nickel-Titanium (NiTi)	Electrical/Thermal	Moderate	Slow (sec)	Bio-robotics, adaptive structures
Electroactive Polymer (EAP)	Ionic/Electronic Polymers	Electrical	High	Moderate	Soft robotics, wearables
Dielectric Elastomer	Silicone/Polyurethane	Electrical	Very High	Fast	Artificial muscles, sensors
Hydraulic Actuator	Hydraulic Fluids	Mechanical	Low	Moderate	Heavy-duty industrial systems
Pneumatic Actuator	Compressed Air	Mechanical	Low	Moderate	Automation, medical haptics

Fig. 2 provides a clear comparison of the energy consumption of Shape Memory Alloy (SMA), Piezoelectric, and Electroactive Polymer (EAP) actuators. This transparent-background visual highlights the significantly lower energy requirements of EAPs, reinforcing their suitability for low-power mechatronic applications. Understanding such comparative performance characteristics is essential when selecting components for energy-efficient system designs.

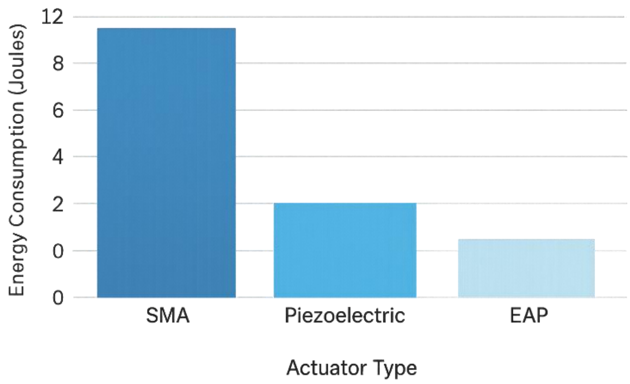

FIG. 2. COMPARATIVE ENERGY CONSUMPTION OF SMART ACTUATORS (SMA, PIEZOELECTRIC, AND EAP) [5–7], [14], [33], [40–42].

Edge computing also boosts energy efficiency by processing data right where it's needed, cutting down delays and speeding up real-time responses. When you pair this with AI algorithms designed for optimization, mechatronic systems can run using minimal resources [40], [42].

Looking ahead, the future of mechatronics really hinges on combining smart materials, AI, and sustainable methods. Making these advanced technologies affordable and widely available is still a challenge, but developments like cobots, soft robotics, and designs running on renewable energy show we're moving towards intelligent, adaptive systems that focus on both great performance and taking care of the environment [40], [41], [42], [43].

IV. INTEGRATION OF RENEWABLE ENERGY IN MECHATRONIC SYSTEMS

Renewable energy is becoming a really important part of designing mechatronic systems, mainly because we're all pushing for technology that's more sustainable, independent, and flexible. With the growing need for low-carbon solutions, you're seeing more robots, automated machines, and smart sensors running on power from sources like solar and wind, or even a mix of both [44].

These green power options are particularly handy for systems that are mobile or located far off the grid—like self-driving vehicles, drones, farming robots, or environmental monitoring stations where reliable power isn't guaranteed. For example, farm drones powered by the sun or robotic buoys using wind power can operate much longer out in the field without needing to stop for a recharge [44], [45].

Hybrid setups, which might combine solar panels, small wind turbines, and energy storage like batteries or supercapacitors, make these systems even more reliable. They can intelligently switch between energy sources based on the weather, ensuring they keep running even if the sun isn't shining or the wind isn't blowing. This flexibility helps avoid sudden shutdowns and significantly extends the time these systems can work on their own [44].

For smart, connected mechatronics (think IoT devices), renewable energy also fits perfectly with energy-conscious networking, where devices often have to work with limited power. By pairing energy harvesting with controls that adapt on the fly, systems can tweak their performance based on the energy they have available in real-time, contributing to their overall sustainability [45].

Even bio-inspired systems, like robotic insects or underwater robots designed to copy nature, are starting to use small renewable power packs and super-efficient components to mimic the efficiency we see in the biological world.Design strategies in this domain prioritize lightweight structures, energy-aware actuation, and intelligent energy management to achieve extended operational lifespans while minimizing ecological impact [46]. Furthermore, the integration of renewable energy supports global decarbonization and climate action initiatives, as these systems operate without fossil fuel dependence. Such eco-friendly design approaches align with the goals of Industry 4.0 and future Smart Cities, where sustainability and autonomy are fundamental attributes [45], [46].

Summary, the confluence of renewable energy technologies and advanced mechatronic systems is fostering a new generation of intelligent, sustainable, and resilient devices capable of operating efficiently in diverse and often challenging environments. [46].

Fig. 3 illustrates the integration of renewable energy sources into modern mechatronic systems. As shown, solar panels, wind turbines, and hybrid energy modules (highlighted in blue) serve as decentralized and sustainable power supplies for various mechatronic platforms—such as autonomous vehicles, drones, agricultural robots, and environmental monitoring stations (shown in grey). The central integration node represents the control and energy management unit that dynamically balances power inputs and consumption. This schematic highlights the synergy between renewable energy harvesting and intelligent, energy-aware mechatronic design, supporting autonomous operation and ecological sustainability in line with Industry 4.0 initiatives.

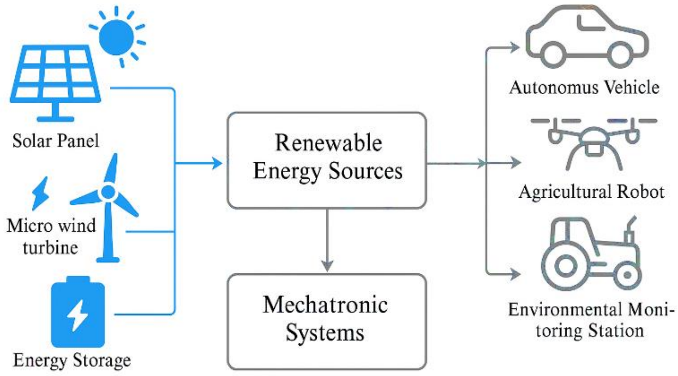

FIG. 3. BLOCK DIAGRAM OF AMBIENT ENERGY HARVESTING TECHNIQUES IN MECHATRONIC SYSTEMS.

V. IOT AND EDGE COMPUTING IN ENERGY-CONSCIOUS MECHATRONICS

The convergence of IoT and edge computing has enabled real-time energy monitoring, decentralized control, and predictive analytics in mechatronic systems. These technologies reduce energy consumption by shifting data processing closer to the devices, thereby lowering latency and minimizing transmission energy costs [47], [48].

Fig. 4 illustrates the mixing of IoT and side computing in power-conscious mechatronic structures. The diagram highlights how cloud-based analytics, facet computing, and smart IoT gadgets collaboratively allow real-time tracking, decentralized control, and predictive choice-making. By processing information locally via part AI, the system minimizes latency and transmission strength, ensuing in optimized electricity efficiency and stronger autonomy in modern mechatronic programs [47], [48].

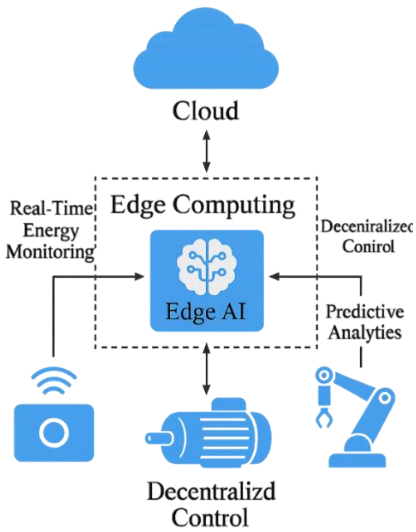

FIG. 4. INTEGRATION OF IOT AND EDGE COMPUTING FOR ENERGY-CONSCIOUS MECHATRONIC SYSTEMS [47], [48].

VI. ENERGY HARVESTING TECHNIQUES

Ambient power harvesting has emerged as a transformative enabler for next-generation mechatronic structures, specifically in applications wherein battery substitute or common maintenance is impractical. By converting clearly going on power from the encompassing environment into usable electrical electricity, energy harvesting technologies facilitate the development of battery-unfastened or battery-augmented mechatronic nodes, making an allowance for prolonged autonomous operation [49].

Piezoelectric harvesters, specifically, are extensively deployed in dynamic environments wherein mechanical vibrations or strain adjustments are gift. These devices convert mechanical strain into electrical energy, making them best for powering microcontrollers, wi-fi sensors, and coffee-electricity actuators in packages like structural health monitoring, industrial automation, and clever wearables [50]. In a comparable vein, thermoelectric turbines employ temperature variations to supply electric strength, making them well-acceptable for structures frequently uncovered to thermal fluctuations, like vehicle engines, heating and cooling units, or heavy commercial equipment. On the other hand, kinetic energy harvesters faucet into motion or vibrations to generate energy, and feature discovered their area in applications including mobile robotics, aerial drones, and even assistive technology like prosthetic limbs—letting them perform longer without depending solely on traditional battery resources [49].

These types of energy harvesting play a critical position in lowering the need for common renovation, specifically in setups which are difficult to attain. Whether it is medical implants, rotating gadget, or environmental sensors situated in remoted or risky regions, those technologies help ensure steady operation with minimal human intervention.They minimize the frequency of human intervention for battery charging or replacement, thereby improving safety, operational uptime, and cost-efficiency [49], [50].

Moreover, the integration of energy-aware control algorithms and low-power circuitry ensures that the harvested energy is used efficiently, maximizing power utilization while maintaining system responsiveness. In IoT-based mechatronic networks, energy harvesting aligns with edge-computing paradigms, where data processing is localized to reduce transmission loads and further conserve energy [50].

In summary, ambient energy harvesting plays a critical role in expanding the deployment range, lifespan, and autonomy of mechatronic systems. As materials science and microelectronics continue to advance, these harvesting technologies will become increasingly compact, efficient, and adaptable to various operational conditions. [50].

To better illustrate the diverse mechanisms and applications of energy harvesting in mechatronic systems, *Fig. 5* presents a block diagram categorizing the primary ambient energy harvesting techniques. It highlights the core types—piezoelectric, thermoelectric, and kinetic harvesters—and their respective roles in enabling autonomous, low-maintenance operation.

This visual representation supports the conceptual understanding of how each method contributes to powering smart, distributed, and mobile mechatronic nodes.

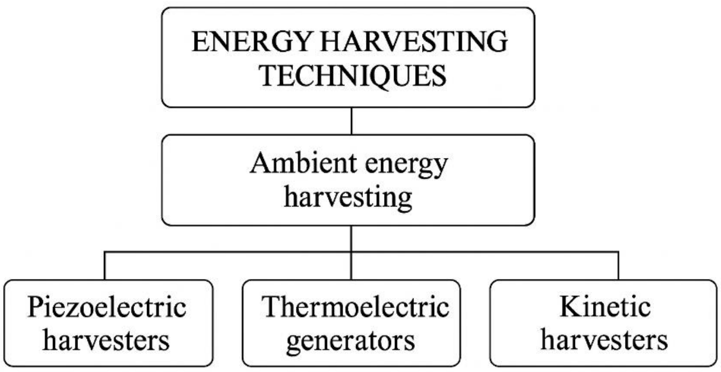

FIG. 5. BLOCK DIAGRAM OF AMBIENT ENERGY HARVESTING TECHNIQUES IN MECHATRONIC SYSTEMS.

VII. THERMAL MANAGEMENT AND WASTE ENERGY UTILIZATION

Advanced thermal management strategies aim to dissipate or recycle waste heat to improve system efficiency and durability. Techniques include passive cooling, heat pipe systems, and thermoelectric generators that convert waste heat into usable energy. These methods are vital for high-performance mechatronic devices, where thermal overload can degrade components and reduce operational lifespan [17], [24].

To demonstrate the practical implementation and impact of energy-efficient strategies in real-world settings, a range of case studies from recent literature is reviewed. These examples span diverse domains—including manufacturing, healthcare, logistics, and aerospace—highlighting how specific techniques such as energy recovery, AI-based control, and smart materials contribute to measurable energy savings.

Fig. 6 illustrates superior thermal management and waste power utilization strategies in mechatronic systems. It highlights key strategies along with passive cooling, heat pipe structures, and thermoelectric mills, all aimed toward improving overall performance and durability by means of mitigating thermal overload. This schematic also connects these methods to their applications in high-performance devices, emphasizing their function in improving energy performance and lengthening operational lifespan [17], [24].

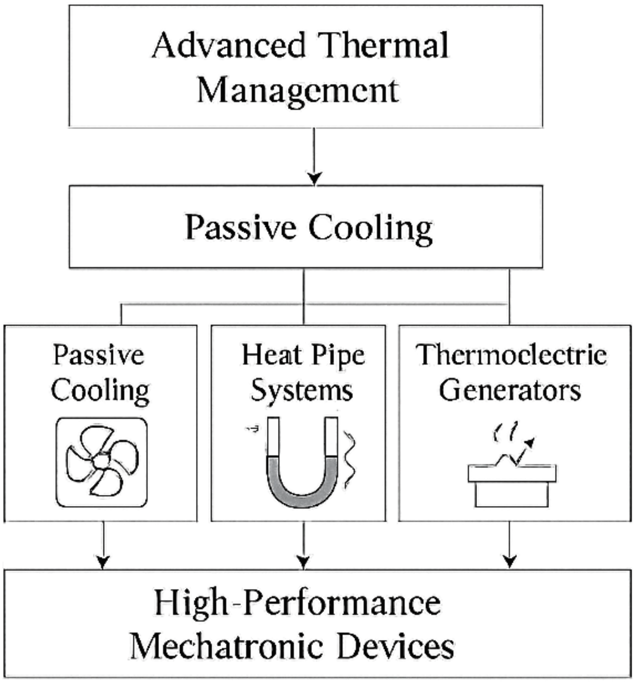

FIG. 6. SCHEMATIC DIAGRAM OF THERMAL MANAGEMENT STRATEGIES AND WASTE ENERGY UTILIZATION IN MECHATRONIC SYSTEMS [17], [24].

VIII. CASE STUDIES AND INDUSTRIAL APPLICATIONS

Real-world implementations across manufacturing, healthcare, and transportation validate the impact of energy-efficient mechatronic solutions. For example, robotic assembly lines using regenerative braking and optimized path planning have demonstrated significant energy savings.

Similarly, medical and wearable devices incorporate energy-harvesting and low-power electronics to maximize usability and battery longevity [46], [51], [52].

Table III summarizes these comparative case studies and the reported outcomes, showcasing the tangible benefits of adopting energy-aware designs in mechatronic systems.

TABLE III. COMPARATIVE CASE STUDIES IN ENERGY-EFFICIENT MECHATRONIC SYSTEMS [7], [9], [20–21], [23], [33], [44–46], [50], [52–53]

Case Study	Domain	Energy-Saving Technique	Reported Outcome
Regenerative braking in robotic arms	Manufacturing	Energy recovery + optimized path planning	~20–25% energy savings per cycle
Piezoelectric wearables for health monitoring	Healthcare	Self-powered sensors with low-power MCU	Extended battery life by 3×
Edge AI-controlled HVAC in smart factories	Industrial HVAC	AI-based predictive control + local processing	30% reduction in energy consumption
Solar-powered autonomous drones	Aerospace	PV cells + adaptive control	40% longer operational time
Smart prosthetic limbs using SMA actuators	Healthcare	Shape Memory Alloy (SMA) actuation	15% lower energy use vs. traditional motors
IoT-enabled robotic forklifts	Logistics	Low-power sensors + task-aware route planning	18% improvement in energy efficiency

IX. CHALLENGES AND FUTURE DIRECTIONS

Current challenges in designing energy-efficient mechatronic systems include balancing energy efficiency with high-performance requirements, as well as managing the complexity of integrated systems. Co-design methodologies—which integrate mechanical and control subsystems from the outset—are emerging as promising approaches to address these challenges [46], [53], [54], [55].

Future research is expected to explore areas such as lifecycle sustainability, adaptive control, and bio-inspired energy-saving strategies. Interdisciplinary collaboration is essential to overcome current technical barriers and to develop scalable solutions.

The key identified challenges include:

1. Lack of standardized frameworks: There is still a gap in the existence of unified standards and frameworks for designing energy-efficient mechatronic systems, calling for the development of cross-industry compatible protocols.
2. Limited integration of energy-efficient trajectory planning with discrete control: There is a need for innovative approaches to improve motion sequencing in multi-axis systems while accounting for dynamic constraints.
3. Handling heat in tight spaces: Effectively managing heat in compact systems is an ongoing struggle. We need better cooling methods and ways to capture and reuse waste heat.
4. Not making the most of energy recovery
5. The challenge of optimizing control for dynamic systems
6. Overlooking lifetime energy use in design
7. Balancing system complexity and energy efficiency
8. Limited integration of renewable power: Expanding research into integrating assets along with solar or wind electricity is important to decorate autonomy and decrease dependence on conventional energy.
9. Lack of co-layout equipment assisting smart substances: There is a need to increase incorporated layout equipment that facilitate the incorporation of those substances into dynamic, thermal, and structural models.

By systematically addressing those studies gaps, the field can circulate in the direction of the improvement of extra sustainable, efficient, and self-reliant mechatronic structures able to assembly the numerous demands of future applications.

To address the multifaceted challenges in energy-efficient mechatronic system design, it is essential to align emerging solutions with current technical barriers and research needs.

Table IV provides a comparative summary highlighting the key challenges, corresponding innovative solutions, and the existing research gaps that must be bridged to advance sustainable, efficient, and autonomous mechatronic systems [46], [53], [54], [55].

TABLE IV. COMPARATIVE SUMMARY OF CHALLENGES, EMERGING SOLUTIONS, AND RESEARCH GAPS IN ENERGY-EFFICIENT MECHATRONIC SYSTEM DESIGN

Key Challenges	Emerging Solutions	Identified Research Gaps
Lack of standardized frameworks	Development of cross-industry protocols	Unified design standards across domains
Integration of energy-efficient trajectory planning	AI-based motion planning, co-design methodologies	Dynamic, multi-axis control integration
Thermal management in compact systems	Advanced cooling techniques, thermoelectric generators	Efficient micro-scale heat recovery solutions
Underutilization of power harvesting & regeneration	Regenerative braking, energy harvesting technologies	Scalable implementation in multi-axis and mobile systems
Complexity in optimizing control for dynamic systems	AI-driven and adaptive control algorithms	Real-time optimization tools for varying conditions
Lack of lifecycle energy evaluation	Digital twins, predictive maintenance	Early-stage integration of sustainability metrics
Balancing hardware/software complexity with energy goals	Bio-inspired designs, variable impedance actuators	Simplified architectures without performance trade-offs
Limited integration of renewable energy sources	Hybrid solar-wind systems, IoT-enabled energy management	Broader adoption in autonomous mechatronic platforms
Lack of co-design tools for smart materials	Integrated dynamic-thermal-structural modeling tools	Seamless incorporation of smart materials in design process

In the pursuit of energy-efficient mechatronic system design, engineers and researchers often face critical trade-offs between performance, cost, complexity, and sustainability. Table V below highlights key conflicting approaches across various domains—such as control strategies, actuator selection, energy sourcing, and system intelligence—while emphasizing the inherent compromises, particularly between cost-effectiveness and operational efficiency. This comparison provides a strategic overview to guide decision-making in balancing technical and economic considerations [1], [5]–[12], [17], [24], [30], [33], [38], [40], [44]–[50], [54].

TABLE V. COMPARISON OF CONFLICTING APPROACHES AND TRADE-OFFS IN ENERGY-EFFICIENT MECHATRONIC SYSTEM DESIGN [1], [5]–[12], [17], [24], [30], [33], [38], [40], [44]–[50], [54]

Aspect	Approach 1	Approach 2	Trade-off Highlighted
Control Strategies	AI-based Optimization (High Efficiency, High Complexity)	PID Control (Low Cost, Low Complexity)	Efficiency vs. Simplicity & Cost
Actuator Selection	Smart Materials (e.g., EAP, Dielectric Elastomers)	Conventional Hydraulic/Pneumatic Actuators	High Efficiency & Lightweight vs. Low Cost & High Power
Energy Source Integration	Renewable Energy (Solar/Wind Hybrid Systems)	Traditional Grid or Battery Power	Sustainability & Autonomy vs. Initial Cost & Reliability

Thermal Management	Thermoelectric Generators (Energy Recovery)	Passive Cooling Techniques	Energy Recycling vs. Simpler, Cheaper Implementation
System Intelligence	Digital Twins & Predictive Maintenance	Scheduled Manual Maintenance	Proactive Efficiency vs. Higher Setup & Operational Costs
Energy Harvesting	Piezoelectric/Kinetic Harvesters (Autonomy, Low Maintenance)	Battery-Powered Systems	Maintenance-Free Operation vs. Lower Initial Costs
Design Methodology	Co-Design (Integrated, Optimized Systems)	Sequential Design Approach	Performance & Efficiency vs. Simpler Development Process
Edge Computing vs. Cloud	Edge AI (Low Latency, Energy Efficient)	Cloud Computing (Centralized, Scalable)	Real-time Efficiency vs. Higher Communication & Processing Costs

Table VI presents a comparison of key technologies.

TABLE VI. TECHNOLOGY MATURITY VS. ENERGY EFFICIENCY IMPACT [1], [5]–[12], [17], [24], [30], [33], [38], [40], [44]–[50], [54]

Technology	Technology Readiness Level (TRL)	Energy Efficiency Impact
PID Control	High	Low to Moderate
AI-based Control	Medium	Very High
Fuzzy Logic Control	High	Moderate
Smart Actuators (EAP, SMA)	Medium	High
Renewable Energy Integration	Medium	High
Digital Twin	Medium	High
Energy Harvesting (Piezo)	Medium	Moderate to High
Edge Computing + IoT	High	High
Thermoelectric Generators	Medium	Moderate
Co-Design Methodologies	Low to Medium	Potentially Very High

X. CONCLUSION

Energy-efficient design in mechatronics has come a long way. We started by making isolated improvements to individual parts, but now the focus is much more on integrating everything and looking at the system as a whole. Progress in hardware, like developing more efficient motors and using lighter materials, has gone hand-in-hand with new software ideas, such as adaptive controls and AI-powered optimization. By combining these hardware and software advancements, we've managed to significantly cut down on energy use without losing performance. Using smart materials and new co-design approaches has also helped make systems more responsive and efficient overall. Today, designing mechatronic systems is increasingly about minimizing energy consumption throughout their entire lifespan.Tools like digital twins are being used to monitor performance and improve efficiency in real-time. The shift toward renewable energy sources, edge computing, and energy harvesting technologies is helping systems become more autonomous and less dependent on external power. However, technical challenges remain—particularly around thermal management and the recovery of waste energy, which are critical in compact systems.

Several research gaps continue to slow progress. A major issue is the lack of standardized design frameworks for energy-efficient systems, leading to inconsistency across different industries. Additionally, combining energy-aware path planning with discrete control—especially in complex, multi-axis environments—remains underdeveloped. Cooling methods and techniques for reusing heat also need further innovation.

Energy regeneration technologies, like systems that recover energy during braking, are still underutilized. Control algorithms for dynamic systems must become more efficient and adaptable to real-time changes. Although lifecycle energy analysis is growing in importance, it’s not yet fully integrated into most design processes; digital twin technologies may help bridge that gap by incorporating energy metrics from the design stage.

Another challenge is managing the balance between system complexity and energy efficiency. Taking cues from nature—such as using bio-inspired actuators—may offer more streamlined and energy-smart solutions. Renewable integration, particularly solar and wind, is still limited in mechatronics and deserves more exploration. Lastly, better design tools are needed to support the seamless use of smart materials within co-design workflows.

Focusing research on these areas will pave the way for the next generation of mechatronic systems—ones that are not only smarter and more efficient but also environmentally sustainable.

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