Article | Received 19 June 2024; Accepted 31 January 2025; Published 21 March 2025
https://doi.org/10.55092/mt20250002

Mechatronics in industry 4.0 and 5.0: advancing synergy, innovations, sustainability, and challenges

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Highlights:

- Mechatronics as a Catalyst for Industry 4.0 and 5.0, enabling smart manufacturing, human-machine collaboration, and sustainable development through interdisciplinary innovation.
- Breakthroughs in Autonomous Systems and AI-driven Solutions, including collaborative robotics, predictive maintenance, and cyber-physical systems for enhanced efficiency and adaptability.
- Emergence of Eco-Mechatronics, integrating environmental sustainability with advanced engineering to foster eco-conscious industrial ecosystems and sustainable technological growth.
- Challenges and Strategic Pathways, addressing scalability in autonomous systems, human-centric design limitations, and sustainability integration through modular systems and AI-driven optimization.
- Future Opportunities in Smart Materials and AI-driven Innovation, advancing bioinspired designs, adaptive materials, and AI-powered systems for next-generation sustainable industry

Abstract: As an interdisciplinary science and engineering paradigm, Mechatronics synergizes diverse engineering and non-engineering disciplines to inspire new ideas, accelerate innovation, and create integrated solutions for complex technological challenges in modern industry and daily life. This paper highlights the critical role of mechatronics in both Industry 4.0 and Industry 5.0, focusing on smart manufacturing systems, sustainable development, and human-machine collaboration. It highlights and discusses significant advancements, including autonomous systems, renewable energy integration, and bioinspired designs, demonstrating notable improvements in efficiency, adaptability, reliability, and interdisciplinary collaboration, reflecting the transformative potential of mechatronics. Practical applications such as AI-driven collaborative robots (Cobots), predictive maintenance systems, and cyber-physical architectures in manufacturing environments illustrate the real-world impact of these innovations. These innovations support more sustainable and efficient operations while reshaping industrial practices. The paper critically evaluates ongoing challenges, including the scalability of autonomous systems, limitations in human-centric technology development, and the integration of sustainability metrics into mechatronic systems. It proposes strategic pathways to address these issues, emphasizing enhanced real-time intelligent decision-making, modular system design, and advanced AI applications. Future opportunities in sustainable technological development are highlighted, driven by

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breakthroughs in AI, robotics, and smart materials. Guided by the mechatronics philosophy of integrated thinking and planning, this paper outlines a roadmap for future innovations. It also highlights the emergence of Eco-mechatronics, an evolution of mechatronics that prioritizes environmental sustainability alongside technological advancement. By integrating Eco-conscious practices with cutting-edge engineering, Eco-Mechatronics presents a transformative approach to addressing global challenges, shaping a more efficient, eco-friendly industrial landscape, fostering sustainable industrial ecosystems, and significantly enhancing human quality of life.

Keywords: mechatronics; synergy; interdisciplinary collaboration; industry 4.0; industry 5.0; smart manufacturing; sustainable development; sustainability; human-centric technologies; AI-driven control systems; cyber-physical systems; autonomous systems; renewable energy; advanced robotics; machine learning; precision agriculture; bioinspired design; interdisciplinary engineering and science

1. Introduction

Mechatronics synergizes mechanical engineering, electronics, control systems, and intelligent computing to address complex technological challenges [1]. By fostering collaboration among these diverse fields, mechatronics has become a driving force for innovation across industries, including manufacturing, healthcare, and robotics [2]. The critical role of Mechatronics in an essential role in Industry 4.0 is evident, where cyber-physical systems (CPS), the Internet of Things (IoT), and big data analytics converge to create highly automated and interconnected manufacturing environments [3].

As industries transition toward Industry 5.0, the emphasis shifts from pure automation to human-machine collaboration. This evolution introduces human-centric technologies to improve well-being and foster sustainability within industrial systems [4]. The goal is to develop manufacturing processes that are more adaptive, safe, and environmentally sustainable, blending human creativity and intelligence with machine efficiency [5].

This paper examines the key contributions of mechatronics to Industry 4.0 and Industry 5.0, focusing on advancements such as autonomous systems, AI-driven robotics, and renewable energy integration [6]. Through interdisciplinary collaboration, mechatronics enables real-time intelligent decision-making, scalable automation, and the creation of advanced human-centric technologies [7]. Practical applications, such as AI-powered collaborative robots (Cobots) and predictive maintenance systems, demonstrate the transformative impact of these innovations in improving operational efficiency and reducing environmental footprints [8]. Furthermore, the evolution of EcoMechatronics integrates sustainability into technological progress, addressing environmental concerns within industrial ecosystems and aligning with the global transition toward greener technologies.

Despite these advancements, significant challenges remain. Scaling autonomous systems and addressing limitations in human-centric technology development are ongoing obstacles. This paper explores strategies to overcome these issues, including modular design for scalability and the use of advanced AI technologies to enhance human-machine collaboration [9]. Furthermore, it identifies future opportunities for sustainable technological development, highlighting the role of EcoMechatronics, AI, robotics, and materials science in creating eco-friendly, efficient industrial systems.

2. The power of synergy in mechatronics

In mechatronics, synergy goes beyond traditional integration by focusing on the active interaction between subsystems, resulting in performance that exceeds the sum of their individual contributions [1]. Instead of simply combining components, synergy in mechatronics promotes real-time coordination among systems, driving advancements that cannot be achieved through conventional methods. An excellent example of this concept is bioinspired design in robotics, where nature-inspired solutions improve system efficiency. This approach demonstrates how the combination of biology, engineering, and computing leads to major breakthroughs in robotic systems that adapt to complex and changing environments [10].

This synergy is essential in robotic automation, where the integration of AI-based control systems and precision sensors enhances manufacturing efficiency and reduces waste [2,6]. These systems are designed to be highly adaptive and self-optimizing, responding to real-time data to improve both performance and resource management.

Table 1. Conventional integration *vs.* system synergy.

Aspect	Traditional Integration	System Synergy
Approach	Combining separate components	The dynamic interplay between components
Performance	The sum of individual parts	Superior to the sum of parts
Approach	Combining separate components	The dynamic interplay between components
Performance	The sum of individual parts	Superior to the sum of parts
Innovation	Incremental improvements	Significant innovations and enhancements
Real-World Example	Basic assembly line automation	AI-powered collaborative robots adapting to real-time data
Adaptability	Limited to component capabilities	Enhanced by seamless interaction
Reliability	Dependent on individual reliability	Increased through holistic integration
Efficiency	Isolated optimizations	Integrated system-wide efficiency through real-time feedback
Flexibility	Rigid and fixed	Adaptive and flexible
Communication	Sequential information exchange	Concurrent, real-time, integrated communication
Design	Independent design efforts	Collaborative and integrated design
Functionality	Basic and singular	Multi-functional and dynamic systems
Smartness	Limited automation	Intelligent, AI-driven adaptive systems
Sustainability	Conventional approaches	Environmentally optimized solutions, reducing waste and energy
Human-Robot Interaction (HRI)	Limited or absent	Seamless collaboration with humans in real-time tasks
Scalability	Challenging to scale	Easily scalable and expandable
Cost Efficiency	Higher long-term costs	The lower total cost of ownership due to improved efficiency

The difference between traditional integration and system synergy lies in their outcomes. Traditional integration connects separate components to function together, while system synergy focuses on continuous interaction and real-time feedback, enabling innovations that go beyond isolated improvements. Table 1 provides a detailed comparison, showing how system synergy leads to better adaptability, scalability, and sustainability.

Papakostas *et al.* [8] describe how integrating AI and machine vision into mechatronics improves the real-time decision-making ability of industrial robots, enabling them to work effectively in dynamic and unpredictable environments. This development represents a shift from Industry 4.0, where automation is the main goal, to Industry 5.0, which emphasizes collaboration between humans and robots and aims for sustainable practices. In Industry 5.0, collaborative robots (Cobots) play an important role in creating manufacturing systems that are more flexible and environmentally responsible, allowing humans and machines to work together seamlessly [1,2,8,11,12].

3. Mechatronics and industries 4.0 and 5.0

Mechatronics plays a central role in advancing Industry 4.0 by enabling the creation of cyber-physical systems (CPS) that integrate real-time data, IoT, and AI to develop smart manufacturing environments. These systems allow for predictive maintenance, self-optimization, and real-time monitoring, which significantly improve efficiency and reduce downtime [4,6]. For example, Siemens' use of digital twins in their smart factories provides real-time insights, enabling manufacturers to predict machine failures before they occur and reduce operational costs [9]. The integration of CPS allows smart factories to autonomously adjust production schedules, monitor machine health, and optimize energy use, ensuring seamless operations [3].

In Industry 4.0, mechatronics significantly impacts smart manufacturing, where the combination of IoT, AI, and robotics drives intelligent systems that enhance real-time data collection and informed decision-making. By automating physical processes, CPS enables production lines to be optimized for efficiency and scalability [7]. IoT-connected sensors in automated machinery continuously monitor production quality and energy consumption, ensuring sustained improvements.

As industries progress toward Industry 5.0, the focus shifts beyond automation and digitization to creating human-centric solutions. In this phase, mechatronics facilitates human-robot collaboration, where AI-driven systems work alongside humans to improve productivity, safety, and job satisfaction. Sustainability becomes a key priority, with mechatronics driving technologies that reduce the environmental impact of industrial activities by incorporating renewable energy systems and resource-efficient processes [8]. For The development of collaborative robots (Cobots) emphasizes creating safe, adaptive working environments where humans and machines collaborate effectively [9].

Complementary attributes of industry 4.0 and industry 5.0

Industries 4.0 and 5.0 represent distinct yet complementary phases of industrial transformation, each bringing unique innovations to how industries operate. Industry 4.0 focuses on digitization, automation, and integrating CPS, IoT, and data analytics, while Industry 5.0 emphasizes human-centric innovations and sustainability.

Industry 5.0 builds on the technological advancements of Industry 4.0 by incorporating human-machine collaboration and prioritizing the reduction of the environmental footprint of manufacturing activities. This is achieved by fostering collaboration between humans and machines, implementing renewable energy solutions, and adopting circular economy practices to create eco-friendly production processes [13].

The transition from Industry 4.0 to Industry 5.0 reflects a shift in priorities—from improving efficiency and scalability through automation to ensuring technology addresses human well-being, environmental sustainability, and personalized production needs. This complementary relationship enables manufacturers to optimize performance while adopting innovative, human-friendly, and eco-conscious practices.

Both paradigms are interconnected in terms of automation, data utilization, and sustainability. Industry 4.0 establishes the technological foundation for automated and smart systems, while Industry 5.0 enhances this foundation with a focus on collaboration and sustainability. Table 2 highlights the complementary attributes of these two paradigms. Both paradigms work together in terms of automation, data utilization, and sustainability, as shown in Table 2, which highlights their respective and complementary attributes. Industry 4.0 establishes the foundation of automated and smart systems, which is further enhanced by Industry 5.0's focus on human collaboration and sustainable innovation.

Table 2. Complementary attributes of industry 4.0 and industry 5.0.

Attribute	Industry 4.0	Industry 5.0
Automation	Robotic automation and smart manufacturing	Collaborative robots (Cobots) working with humans
Data Utilization	Real-time data analysis via CPS and IoT	AI and machine learning to enhance decision-making
Human Involvement	Minimal, mostly machines managing production	Human-machine collaboration for enhanced productivity and safety
Sustainability	Energy-efficient systems but limited focus	Renewable energy, circular economy, and eco-friendly processes
Customization	Mass customization through smart systems	Personalized production for human needs via collaborative systems
Innovation Focus	Technological innovations in automation	Human-centric innovations (safety, well-being) and adaptive systems
Job Satisfaction	Limited to managing machines	Higher job satisfaction through interaction with Cobots and AI-enhanced workflows
Predictive Maintenance	AI diagnostics and real-time monitoring	AI-powered Cobots assisting in maintenance tasks
Energy Efficiency	Smart energy grids and resource management	Renewable energy integration and bioinspired design
User Experience	Systems optimize performance with a limited focus on UX	Focus on improving human experience and engagement in production

4. Human-centric values and sustainability in mechatronics

In the context of Industry 5.0, mechatronics has progressed beyond advancing automation to embrace human-centric values and sustainability. It now plays a pivotal role in integrating emerging concepts such as EcoMechatronics, bioinspired design, ecosystem principles, and the circular economy. These developments aim to balance technological innovation with human well-being and environmental responsibility [14,15].

4.1. Ecomechatronics: a sustainable approach

Eco-mechatronics extends traditional mechatronics by embedding environmental sustainability principles. It emphasizes designing systems and technologies to minimize environmental impact throughout the product lifecycle by improving energy efficiency, reducing resource consumption, and minimizing waste. This approach aligns with the circular economy model, where resources are reused and recycled rather than discarded [16].

The development of solar-powered robots integrated into production lines enhances efficiency but also promote sustainability by reducing reliance on fossil fuels, a key goal of Industry 5.0 [16]. The contributions of Eco-mechatronics to Industry 4.0 and Industry 5.0 are complementary, as shown in Table 3, where key synergies are highlighted.

Table 3. Summary to the contributions of Ecomechatronics in industry 4.0 and industry 5.0.

Aspect	Ecomechatronics in Industry 4.0	Ecomechatronics in Industry 5.0
Sustainability	Focus on minimizing energy consumption and optimizing manufacturing processes to reduce waste and increase efficiency.	Emphasis on designing systems that contribute to a circular economy, with renewable energy integration and low waste production.
Automation and Efficiency	Automated cyber-physical systems (CPS) designed to optimize real-time manufacturing, reducing downtime and energy usage.	AI-driven systems that learn from human inputs, improving both efficiency and worker satisfaction. Enhanced predictive maintenance to extend product life.
Human-Centric Design	Limited focus on human-centric aspects, with automation primarily aiming to improve manufacturing processes and reduce costs.	Emphasis on human-robot collaboration (e.g., cobots) designed for worker safety, comfort, and higher productivity. Technologies are co-developed to align with human needs.
Bioinspired Systems	Incorporates bioinspired designs for enhanced material efficiency and energy reduction in production equipment.	Systems designed to mimic nature not only in materials but also in adaptive processes, creating more flexible and responsive manufacturing systems.
Circular Economy Integration	Some focus on modular design for ease of repair and upgrading, supporting long-term sustainability.	Fully integrated circular economy principles, where components are designed to be reused, remanufactured, or recycled to reduce environmental impact.
Resource Efficiency	Focus on optimizing resource use through data analytics, reducing energy consumption during production cycles.	Closed-loop systems that repurpose waste materials, ensuring minimal waste output and maximizing resource reutilization.
Renewable Energy Integration	Increasing integration of renewable energy into manufacturing processes to reduce reliance on fossil fuels.	Full renewable energy integration, with manufacturing systems powered by solar, wind, or other renewable sources, drastically cutting emissions.
Maintenance and Lifespan	Predictive maintenance enabled by real-time data, reducing machine failure and extending equipment life.	Machines and systems designed for long lifecycles, with modular components that can be easily repaired or replaced to reduce waste.
AI and Machine Learning	AI optimizes production and resource allocation, learning from system data to improve energy efficiency and reduce downtime.	AI integrated with human inputs to create adaptive systems that continuously improve both performance and sustainability based on real-world feedback.

4.2. Bioinspired design and ecosystem principles

Bioinspired design takes inspiration from natural systems to create and develop innovative, sustainable technologies. In mechatronics, this approach results in machines that are energy-efficient, reliable, and adaptable, mimicking nature's resourcefulness [15,17]. For example, robotic systems inspired by lightweight yet strong structures in nature lead to more efficient use of materials.

These systems align with ecosystem principles, where waste from one process becomes a resource for another. In Industry 5.0, bioinspired closed-loop systems ensure minimal waste and maximize material reuse, supporting sustainability and resource efficiency [17].

4.3. Circular economy and mechatronics

The circular economy framework emphasizes products, components, and materials at their highest utility for as long as possible. Mechatronics supports the shift from a linear economy (make-use-discard) to a circular one by enabling predictive maintenance, modular design, and remanufacturing. These practices ensure products can be repaired, refurbished, or reused, minimizing waste [14,18]. Cobots with modular components are designed for easy replacement or upgrading, extending their lifespan while reducing waste. Real-time monitoring systems further enhance sustainability by predicting failures and scheduling maintenance efficiently [15].

4.4. Human-robot collaboration and sustainable manufacturing

In Industry 5.0, human-robot collaboration enhances the sustainability and efficiency of manufacturing processes. By integrating human intelligence with AI-driven systems, mechatronics enables technologies that adapt to human needs while reducing the environmental footprint of industrial operations. This shift fosters a more sustainable industrial ecosystem, improving worker well-being and aligning manufacturing processes with the principles of the circular economy [19,20].

5. Contributions and impacts of mechatronics to industry 4.0 and 5.0

In the context of Industry 5.0, mechatronics has evolved beyond advancing automation. It now plays a crucial role in integrating human-centric values and sustainability, aligning with emerging concepts such as Eco-Mechatronics, bioinspired design, ecosystem principles, and the circular economy. These developments focus on balancing technological innovation with human well-being and environmental responsibility [14,15].

5.1. Space exploration

In space exploration, NASA's Curiosity and Perseverance rovers utilize high-precision actuators, LiDAR sensors, and environmental sensors to perform complex navigation and data collection tasks in extreme environments. These mechatronic systems enable the rovers to autonomously navigate Mars' surface, collect soil samples, and transmit real-time data back to Earth, expanding our understanding of the Martian environment [21].

A deeper analysis of the rover’s LiDAR and sensor fusion algorithms highlights how mechatronics optimizes real-time terrain mapping and obstacle avoidance, which are key challenges in extraterrestrial environments. Additionally, control algorithms, such as PID control for actuator movement, ensure precise navigation in challenging conditions. These systems exemplify how mechatronics is pivotal in addressing the demands of space exploration.

5.2. Automotive industry

In the automotive sector, Tesla’s Autopilot system is a prime example of how mechatronics enables autonomous driving. By integrating camera-based vision, radar systems, and sensor fusion algorithms, the system allows vehicles to navigate safely and efficiently in real-world conditions [22].

Sensor fusion techniques, including the Kalman filter and advanced methods like particle filters or AI-driven algorithms, enable the integration of camera and radar data and other sensory data to enhance decision-making and safety. The choice of technique depends on system requirements, such as the need to handle non-linear dynamics or real-time constraints.

5.3. Smart manufacturing and industry 4.0

In smart manufacturing, mechatronics facilitates the development of cyber-physical systems (CPS) that monitor production processes in real time, leading to greater precision and resource efficiency. Siemens’ Digital Factory integrates IoT, robotics, and AI algorithms to automate assembly lines and predict maintenance needs, significantly reducing downtime [23]. Providing further detail on how predictive maintenance uses sensor data to preemptively address potential equipment failures via machine learning models (e.g., recurrent neural networks for time-series analysis) can showcase the power of data-driven maintenance strategies in smart factories.

In smart manufacturing, mechatronics drives the development of cyber-physical systems (CPS) that monitor production processes in real-time, leading to greater precision and resource efficiency. Siemens’ Digital Factory integrates different range of IoTs, robotics, and AI algorithms to automate assembly lines and predict maintenance needs, significantly reducing downtime [23,24].

Predictive maintenance systems use sensor data and machine learning models, such as recurrent neural networks (RNNs) for time-series analysis, to address potential equipment failures preemptively. Additionally, Nano-manufacturing technologies like IBM's 3D Nano-printing systems illustrate the role of mechatronics in achieving precision at the atomic level and push the boundaries toward miniaturization in production, with atomic force microscopes (AFM) used for accurate manipulation and assembly [24].

5.4. Renewable energy and sustainability

In renewable energy, mechatronics enhances the performance of wind turbines and solar tracking systems. Siemens Gamesa’s wind turbines use adaptive control systems to optimize power generation based on real-time wind conditions, while solar farms rely on automated solar tracking systems to maximize energy capture throughout the day [25,26].

Technologies like fuzzy logic controllers or proportional-integral-derivative (PID) controllers optimize turbine control, improving energy generation. Additionally, smart grids equipped with mechatronic components enhance energy distribution and support renewable energy integration by using AI and IoT for real-time load management.

Battery energy storage systems (BESS), optimized by mechatronic algorithms for energy balancing, demonstrate promising trends in sustainable energy management. These innovations illustrate how mechatronics contributes to the efficiency and sustainability of the entire energy ecosystem.

5.5. Medical field

In healthcare, robotic-assisted surgery systems, such as the Da Vinci Surgical System, use high-precision actuators and robotic arms to perform minimally invasive surgeries with enhanced accuracy, reducing patient recovery times and improving outcomes [27].

Haptic feedback mechanisms, controlled using proportional-derivative (PD) control systems, allow real-time sensory feedback for surgeons, enhancing precision and responsiveness. Additionally, bioinspired designs, such as snake-like robotic arms, mimic natural flexibility to provide access to previously unreachable surgical areas [28,29].

Advanced prosthetics equipped with electromyographic (EMG) sensors further highlight mechatronics integration in healthcare. These sensors detect electrical signals from muscles, transmitting them to microcontroller-based systems that control prosthetic movements. Artificial tendons and soft materials inspired by biological systems mimic the natural dynamics of the human body, improving quality of life for amputees [30,31].

5.6. Precision agriculture

In agriculture, John Deere's autonomous tractors and precision farming technologies leverage GPS-guided systems, sensor arrays, and AI-driven control systems to enhance efficiency. These systems optimize water and fertilizer usage while maximizing crop yields, contributing to sustainable farming practices [32].

Technologies such as Variable Rate Technology (VRT) utilize real-time data from sensors to adjust planting depth, seeding rates, and chemical applications based on soil and crop conditions [4]. Mechatronic systems further incorporate computer vision and drone-based monitoring to assess crop health, detect weeds, and optimize irrigation. These advancements underscore how mechatronics is driving precision and sustainability in agriculture [33].

6. Bioinspired design and ecomechatronics: synergies for a sustainable future

Bioinspired design plays a crucial role in advancing EcoMechatronics, a field focused on the development of sustainable technologies that minimize environmental impact. By drawing inspiration from nature's efficiency and resilience, bioinspired design offers innovative pathways to energy efficiency, resource conservation, and sustainable development. This approach is perfectly aligned with the principles of EcoMechatronics, which emphasize the creation of eco-friendly systems that contribute to a circular economy and promote the green evolution of technology.

6.1. Energy efficiency and resource optimization

One of the most significant contributions of bioinspired design to EcoMechatronics is in the area of energy efficiency. Systems inspired by natural processes—such as solar energy technologies modeled on photosynthesis—have led to the development of bioinspired solar panels with improved energy capture and minimal resource wastage [34]. Similarly, bioinspired flapping-wing drones, which mimic the flight mechanics of birds, consume less energy than traditional fixed-wing drones, making them ideal for applications in environmental monitoring and precision agriculture where energy efficiency is critical [35].

Moreover, bioinspired aerial robots, such as morphing tail designs, improve flight maneuverability and stability, further optimizing energy efficiency in robotic applications.

By integrating energy-harvesting technologies inspired by nature, such as piezoelectric materials that convert mechanical vibrations into electrical energy, mechatronic systems can capture and utilize ambient energy, further reducing their dependence on external power sources [36]. Additionally, honeycomb-structured materials inspired by natural architectures offer enhanced mechanical properties for energy-efficient lightweight structures in robotic and mechatronic applications [37]. These align with the EcoMechatronics principle of resource optimization, where systems are designed to minimize waste and maximize the use of renewable resources.

6.2 Sustainable materials and circular economy

In line with EcoMechatronics' emphasis on sustainability, bioinspired design is driving the development of biodegradable and self-healing materials. For example, materials inspired by spider silk are being used to create lightweight yet durable components that require fewer raw materials and are biodegradable, reducing environmental impact in sectors such as aerospace and biomedical engineering [38]. Self-healing polymers, modeled after the regenerative capabilities of natural tissues, allow for longer-lasting products, reducing the need for replacements and contributing to a more sustainable lifecycle for mechatronic systems [39]. These advancements have been particularly significant in the field of soft robotics, where self-healing materials enhance durability and functionality.

These materials support the creation of a circular economy by promoting waste reduction and enabling the continuous reuse of resources. In precision agriculture, bioinspired systems that mimic natural nutrient cycles optimize resource use, helping farmers reduce water and fertilizer consumption, thus minimizing environmental pollution and promoting sustainable farming practices [40].

6.3. Environmental monitoring and remediation

EcoMechatronics aims not only to minimize the environmental footprint of technologies but also to develop systems that actively contribute to environmental restoration. Bioinspired robotic systems, particularly swarm robotics modeled on the collective behavior of social insects, are being deployed for tasks such as environmental cleanup and ecosystem monitoring [41]. These robots can work together to clean up pollutants or manage invasive species, replicating the efficiency of ants and bees in their natural habitats.

Additionally, bioinspired sensors, which mimic the sensitivity of animal sensory organs, are being developed to monitor air quality, water pollution, and soil health. These sensors are integrated into broader mechatronic systems that provide real-time data for environmental management, ensuring that resource use is optimized and environmental damage is minimized [42]. Furthermore, biomimetic approaches are also influencing the development of advanced prosthetic hands, where myoelectric control and bioinspired tendon structures enhance dexterity and adaptability [43, 44].

6.4. Towards a green future

The integration of bioinspired design within EcoMechatronics represents a powerful approach to achieving sustainable technological growth. By combining the principles of biomimicry with energy-efficient systems and sustainable materials, mechatronic systems can reduce their environmental impact while enhancing functionality. Future innovations in areas such as biohybrid systems, which merge biological components with mechatronic devices, promise even greater strides in developing renewable technologies and promoting a green economy [45]. Soft robotics, which utilize bioinspired designs to achieve adaptability and flexibility, are also expected to play a major role in sustainable automation [46].

As bioinspired design continues to evolve, it will play a central role in advancing the goals of EcoMechatronics, helping to create a future where technologies are not only more efficient and adaptable but also more aligned with the sustainability principles that are critical for a green future.

Bioinspired design plays a crucial role in advancing EcoMechatronics, a field focused on the development of sustainable technologies that minimize environmental impact. By drawing inspiration from nature's efficiency and resilience, bioinspired design offers innovative pathways to energy efficiency, resource conservation, and sustainable development. This approach is perfectly aligned with the principles of EcoMechatronics, which emphasize the creation of eco-friendly systems that contribute to a circular economy and promote the green evolution of technology.

7. Mechatronics and bioinspired design

Mechatronics, by nature an interdisciplinary field, finds new depth and direction through bioinspired design. This approach draws inspiration from biological systems to address complex engineering and problem-solving challenges, creating solutions that are not only innovative but also sustainable. When aligned with the principles of EcoMechatronics, bioinspired design provides an effective pathway toward developing technologies that reduce environmental impact, foster ecosystem balance, and contribute to the circular economy.

7.1. Bioinspired design: addressing engineering challenges through nature's principles

The synergy of bioinspired design within mechatronics allows scientist and engineers to tackle interdisciplinary challenges by bioinspired the design, sensor, structures, material, ecosystems, efficiency, adaptability, and resilience found in nature. The soft robotics inspired by organisms like octopuses or worms have been developed to navigate complex environments. These robots are designed with flexibility in mind, allowing them to operate in confined spaces and challenging terrains, as required in search-and-rescue operations and underwater exploration [34,46,47].

Additionally, bioinspired sensors—modeled after biological sensory systems—have been employed for environmental monitoring. These sensors mimic the sensitive detection abilities of animals and plants, enabling accurate tracking of changes in air quality, water pollution, and soil health. The incorporation of such systems into mechatronic platforms ensures real-time data collection for improved ecosystem management [40,48]. Moreover, bioinspired robotic surgery systems have been developed, incorporating machine learning and AI-driven control mechanisms to enhance precision and adaptability in surgical tasks [49]. These systems leverage soft robotics and adaptive control inspired by biological movement, improving dexterity in minimally invasive procedures while reducing patient recovery times.

7.2. EcoMechatronics: merging sustainability with technological innovation

EcoMechatronics takes bioinspired design a step further by prioritizing sustainability across the entire lifecycle of mechatronic systems, from design and production to use and disposal toward achieving zero waste One critical area where this is evident is in the development of energy-efficient and biodegradable materials, which minimize resource consumption and environmental harm.

For example, materials inspired by spider silk have been engineered for use in robotic actuators and medical devices, offering high durability while being lightweight and biodegradable [50]. These innovations align with the goals of the circular economy, where materials are reused or recycled to minimize waste and promote resource efficiency. In industries such as aerospace and biomedicine, where material performance and environmental impact are key considerations, the application of these bioinspired materials is transforming how products are designed and used [51,52].

7.3. Impact on the circular economy and ecosystem balance

The principles of EcoMechatronics and bioinspired design converge to promote technologies that actively contribute to a circular economy. In this framework, resources are continuously repurposed, and waste is minimized. Mechatronic systems developed with bioinspired materials, such as self-healing polymers and biodegradable components, are designed to last longer and degrade naturally, reducing waste and limiting the need for constant raw material extraction [53].

In the context of renewable energy, bioinspired designs, such as solar panels modeled on the process of photosynthesis, demonstrate nature’s influence on improving energy capture and efficiency. These solar panels capture sunlight more effectively, reducing material waste and promoting sustainable energy production [54]. The development of energy-harvesting technologies like piezoelectric systems, which convert mechanical vibrations into electrical energy, further supports the circular economy by utilizing ambient energy in smart cities and other urban applications, lessening the reliance on non-renewable energy sources [55].

7.4. Utilizing ecosystem principles for sustainability

Bioinspired design also draws from ecosystem principles, where balance, interdependence, and resource efficiency are critical for sustaining life. In mechatronics, these principles are mirrored in the design of smart manufacturing systems, which mimic the symbiotic relationships found in natural ecosystems. For example, autonomous drones and robotic systems used in precision agriculture are designed to optimize resource use by working collaboratively. These systems reduce water and fertilizer usage by delivering targeted treatments based on real-time sensor data, minimizing the environmental footprint of farming while boosting crop yield [56,57].

Furthermore, bioinspired approaches are being applied to develop circular systems in smart cities and modern urban design, where energy, waste, and resources are managed in an integrated manner to reduce environmental impact. Swarm robotics, modeled after the collective behavior of insects such as ants, allows robots to cooperate and optimize tasks like waste collection or infrastructure inspection, improving efficiency while minimizing resource use [58].

7.5. Prospects: driving innovation in EcoMechatronics

As we look to the future, the integration of bioinspired design with EcoMechatronics holds promise for addressing some of the world’s most pressing challenges, such as climate change, resource scarcity, and environmental degradation. By developing sustainable mechatronic systems that align with ecosystem principles and contribute to the circular economy, engineers can create technologies that not only perform better but also actively reduce their environmental footprint [59].

For example, ongoing research into biohybrid systems, which merge biological and mechatronic components, is set to revolutionize industries ranging from medicine to energy. These systems could be used to power biodegradable robots or create self-sustaining energy sources, driving sustainability while fostering innovation in green technology [60,61]. Additionally, bioinspired prosthetic limbs are evolving rapidly, integrating advanced biomimetic control mechanisms that enhance user adaptability and movement precision [62].

8. Future prospects and emerging trends

Mechatronics is set to evolve significantly, bringing transformative advancements to various sectors. The integration of edge computing, autonomous systems, renewable energy technologies, and bioinspired design will drive this transformation. These trends will push the boundaries of efficiency, safety, and adaptability, with mechatronics playing a key role in these innovations.

8.1. Autonomous systems and robotics

Mechatronics is critical in developing next-generation autonomous systems such as vehicles, drones, and robots. These systems will incorporate advanced AI algorithms and real-time sensor fusion, enabling them to operate efficiently in dynamic and unpredictable environments. Next-generation autonomous vehicles are expected to utilize swarm intelligence to improve traffic coordination and safety [60]. In the agricultural sector, AI-driven drones will be capable of real-time crop monitoring and targeted interventions, reducing resource use while increasing yield [61].

8.2. Medical devices and prosthetics

Biomedical mechatronics will continue revolutionizing the medical field by driving innovation in robotic surgery, prosthetics, and diagnostic systems. Robotic surgical systems like the Da Vinci Surgical System will benefit from enhanced AI integration, allowing for greater precision in minimally invasive surgeries and reducing the risks of complications [49]. Bioinspired prosthetics that mimic natural limb movement will also become more advanced, offering patients improved mobility and functionality. These smart prosthetics, which adapt to user behavior through machine learning, will significantly improve the quality of life for amputees [62].

8.3. Industry 4.0 and industry 5.0: smart manufacturing and human-centric solutions

Industry 4.0 centers on integrating advanced technologies like cyber-physical systems (CPS), IoT, and AI into smart manufacturing environments. This integration enables manufacturers to enhance production processes by collecting and analyzing real-time data, improving flexibility, precision, and decision-making. With these systems, manufacturers can dynamically adjust operations based on current demands, leading to more efficient and scalable production systems. The technologies of AI and automation streamline workflows, reducing waste and downtime and improving productivity while maintaining high-quality control standards [63].

Industry 5.0, however, shifts the focus from purely efficiency-driven automation to more human-centric approaches. It emphasizes collaboration between humans and machines, where workers and intelligent systems co-create value in more sustainable ways. By integrating renewable energy solutions and focusing on sustainability, Industry 5.0 seeks to minimize environmental impacts, enhance workplace safety, and improve overall well-being. This paradigm promotes a more balanced approach, leveraging human creativity and machine precision to meet environmental and societal goals [64].

Thus, while Industry 4.0 focuses on automation and intelligent manufacturing, Industry 5.0 builds upon this foundation by incorporating human-centric values and sustainable practices, creating a more resilient and environmentally conscious future for industries.

8.4. Energy-efficient and sustainable systems

Sustainability will be a core focus in the future development of mechatronics, especially as efforts to create energy-efficient systems become increasingly vital in combating climate change. Mechatronic systems optimized for energy harvesting and resource management will be crucial. For example, advancements in autonomous energy-efficient systems, such as those used in renewable energy infrastructure, can significantly reduce energy consumption while improving overall system performance [15].

In environmental monitoring, mechatronic systems with advanced sensing technologies will provide data on real-time pollution and climate variables. These systems will be instrumental in improving ecological resource management and ensuring the successful implementation of sustainable development practices [65].

Sustainability is becoming increasingly important in the future development of mechatronics. Mechatronics is key to designing and integrating energy-efficient systems that mitigate climate change. Innovations in mechatronic systems, such as renewable energy integration, are critical for ensuring that industries use energy more efficiently. These systems can optimize energy consumption through intelligent control systems and renewable sources like wind and solar power, making manufacturing greener and more cost-effective [66]. Furthermore, autonomous mechatronic systems are being deployed for environmental monitoring, using energy-efficient sensors to track pollution and climate conditions in real time, supporting sustainable development goals [65].

8.5. Bioinspired design as a driver of future innovation

The future of mechatronics will be driven by the integration of bioinspired design, which mimics nature’s efficiency and adaptability to create advanced, sustainable technologies. For example, bioinspired robots modeled after insects are expected to perform complex tasks in environments where traditional robots cannot operate, such as deep-sea exploration or hazardous material handling [67]. Additionally, these robots will be designed to be msore energy-efficient, in line with the principles of EcoMechatronics, further promoting the development of technologies that are in harmony with the environment [16,19,68].

9. Conclusion

Mechatronics remains a transformative and interdisciplinary potential force in shaping the future of technology, utilizing its foundational principles to address complex challenges and drive sustainable innovation across diverse domains. By synergizing bioinspired design, artificial intelligence (AI), edge computing, smart sensors and actuators, advanced materials, and the principles of EcoMechatronics, this field continues to revolutionize industries such as manufacturing, medicine, transportation, and renewable energy. As mechatronics evolves, it adopts innovative solutions while proactively addressing emerging challenges, ensuring its adaptive impact and progressive contributions to a sustainable and technologically advanced future.

These advancements, however, are not without their hurdles. Therefore, to fully realize its transformative potential and its spectrum of a rapidly evolving spectrum of concepts and synergies, mechatronics must address key challenges, bridge interdisciplinary knowledge gaps, and drive continuous improvement in both sustainability and innovation:

9.1. Overcoming challenges and bridging knowledge gaps

Mechatronics faces critical challenges that must be resolved to secure its role as a cornerstone of technological progress. These include achieving seamless system synergies, fostering interdisciplinary collaboration, advancing smart functionalities with embedded real-time decision-making and learning, and ensuring cybersecurity resilience. Tackling these issues effectively will unlock its full potential and enable groundbreaking advancements across industries:

9.1.1. System synergy and scalability

The increasing complexity of mechatronic systems demands robust synergy frameworks that ensure all components interact harmoniously to enhance overall performance. Modular architectures offer flexibility for scalability and adaptability, while digital twins provide virtual replicas that enable real-time monitoring, predictive analytics, and iterative optimization. Additionally, predictive maintenance methodologies leverage data-driven insights to proactively address system inefficiencies and reduce downtime, ensuring that mechatronic systems remain resilient and future-ready.

9.1.2. Interdisciplinary collaboration

A true innovation in mechatronics relies on synergy across diverse disciplines, including biology, computing, mechanical engineering, and materials science. Fostering this synergy requires targeted investments in interdisciplinary education, cross-domain training, and the establishment of collaborative research platforms. These efforts will bridge knowledge gaps, enable the exchange of expertise, and accelerate the development of breakthrough technologies. Encouraging open dialogue among researchers, practitioners, and educators will also cultivate a culture of collaboration that drives innovation.

9.1.3. Cybersecurity resilience

As mechatronic systems become increasingly interconnected and reliant on autonomous technologies, they face heightened exposure to cyber threats. Protecting these systems requires multi-layered cybersecurity strategies, including advanced encryption, AI-driven anomaly detection, and secure communication protocols. Cyber resilience is particularly critical in high-stakes domains like autonomous transportation, healthcare robotics, and smart manufacturing, where system breaches can have severe consequences. Proactively addressing these vulnerabilities will ensure the safety of operations and the trust and confidence of users and stakeholders.

9.2. Synergy between mechatronics and industry 4.0/5.0

The synergy between mechatronics and the emerging industrial paradigms of Industry 4.0 and Industry 5.0 is driving the next wave of technological bWreakthroughs

9.2.1. Industry 4.0

Mechatronics enhances smart manufacturing by integrating cyber-physical systems (CPS), real-time data analytics, and AI-powered solutions. These innovations improve efficiency, flexibility, and decision-making across production lines, enabling manufacturers to respond dynamically to evolving market demands.

9.2.2. Industry 5.0

Mechatronics advances human-centric approaches, where collaborative robots (Cobots) and AI-powered machines work seamlessly alongside humans. This change in thinking emphasizes sustainability, safety, and workforce well-being, ensuring that technology serves societal and environmental objectives while achieving higher productivity and adaptability.

9.3. Sustainable development through bioinspired design

The rise of bioinspired design and EcoMechatronics is redefining the boundaries of sustainable innovation:

(1) Nature-inspired solutions

Drawing from nature’s efficiency, technologies such as self-healing materials, energy-harvesting systems, and biomimetic robots will enable systems that optimize performance while reducing their environmental impact.

(2) Circular economy principles

Innovations rooted in bioinspired design will enhance resource efficiency by minimizing waste and extending the lifecycle of mechatronic systems. Industries can align their operations with sustainability goals by adopting biodegradable materials, closed-loop manufacturing processes, and adaptive systems.

9.4. Laying the foundation for breakthroughs in technological innovation

As mechatronics continues to evolve, its focus on system synergy, rather than mere integration, will remain its defining strength:

(1) Adaptable systems and smart materials

Future mechatronic systems will incorporate autonomous solutions, intelligent control systems, and smart materials capable of self-optimization and self-repair, ensuring resilience in complex environments.

(2) Bridging knowledge gaps

The holistic approach of mechatronics, integrating mechanical engineering, AI, control systems, and materials science, will bridge existing knowledge gaps and foster interdisciplinary innovation.

(3) Driving visionary developments

As it embraces emerging technologies, mechatronics will remain pivotal in addressing global challenges, such as climate change, resource scarcity, and public health crises. By combining technical expertise with a commitment to sustainability, the field will pioneer innovations that redefine societal progress.

Conflicts of interests

The author declares no conflicts of interest.

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