

Editorial

Artificial Intelligence and Control Systems for Industry 4.0 and 5.0: Recent Advances, Knowledge Gaps, and Future Research Directions

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1. Introduction

Artificial intelligence, control systems, industrial IoT, digital twins, and cyber-physical production systems are reshaping the technological foundations of advanced manufacturing. This Editorial synthesizes the contributions published in the Special Issue “Artificial Intelligence and Control Systems for Industry 4.0 and 5.0” and positions them within the transition from highly connected Industry 4.0 environments to more human-centric, sustainable, and resilient Industry 5.0 systems. The papers in this Special Issue address cloud-based robotic vision, multi-agent systems and Asset Administration Shells, AI-driven value chains, deep reinforcement learning for robotic manipulation, multi-cloud data latency, decentralized manufacturing control, machine-learning-based warehouse optimization, smart IoT sensing for energy efficiency, and secure software-defined industrial networks. Together, these contributions highlight both the maturity of AI-enabled industrial applications and the remaining challenges associated with trustworthiness, interoperability, cybersecurity, scalability, real-time control, and socio-technical integration. Future research should therefore prioritize verifiable AI for closed-loop control, standardized digital-twin infrastructures, edge-cloud orchestration, human-in-the-loop autonomy, cyber-resilient architectures, and sustainability-aware industrial intelligence.

Industry 4.0 established a paradigm in which manufacturing systems are increasingly connected, data-driven, and integrated through cyber-physical systems, industrial IoT, cloud services, automation technologies, and advanced analytics. However, the transition to Industry 5.0 has widened the scope of industrial digitalization. Rather than focusing only on connectivity and efficiency, current industrial research increasingly emphasizes human-centricity, sustainability, resilience, trustworthy autonomy, and the capacity of production systems to adapt to disturbances while preserving social and environmental value [1].

In this context, artificial intelligence and control systems are not independent technological domains. Their convergence is essential for the design of adaptive, autonomous, and collaborative industrial systems. AI provides perception, prediction, diagnosis, optimization, and decision-support functions, whereas control systems translate these functions into



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safe, timely, and reliable action in physical production environments. The integration of both domains is therefore central to the next generation of industrial robots, smart factories, digital twins, distributed manufacturing systems, energy-aware infrastructures, and secure industrial networks.

The Special Issue “Artificial Intelligence and Control Systems for Industry 4.0 and 5.0” was launched to collect recent advances at this intersection. The nine contributions published in the Special Issue demonstrate that the field is progressing from conceptual digitalization to deployable architectures, algorithms, and industrial use cases. At the same time, they show that major scientific and engineering challenges remain open, particularly when AI is embedded in cyber–physical systems that require real-time performance, explainability, interoperability, safety, cybersecurity, and long-term maintainability.

2. Contributions in This Special Issue

The contributions in this Special Issue can be grouped into four complementary research streams: AI-enabled perception and robotics, digital twins and decentralized industrial intelligence, data-driven optimization and industrial infrastructures, and sustainability- and security-oriented Industry 5.0 systems.

Table 1 summarizes the main themes and scientific contributions of the papers published in this Special Issue. These contributions can be grouped into four complementary research streams: AI-enabled perception and robotics, digital twins and decentralized industrial intelligence, data-driven optimization and industrial infrastructures, and sustainability- and security-oriented Industry 5.0 systems.

Table 1. Overview of the main themes and contributions of the papers published in the Special Issue “Artificial Intelligence and Control Systems for Industry 4.0 and 5.0”.

Reference	Main Theme	Contribution to the Special Issue
[2]	Cloud-based robotic vision	Assesses cloud vision services for industrial robot perception and object sorting, linking AI perception with industrial robotic execution.
[3]	Multi-agent systems and AAS	Discusses the role of multi-agent systems in creating active Asset Administration Shell Type 3 entities for more autonomous industrial digital twins.
[4]	AI-driven sustainable value chains	Examines how AI, digital twins, and cognitive automation can support predictive maintenance, circularity, and resilient value-chain transformation.
[5]	Deep reinforcement learning for robotics	Investigates adaptive robotic grasping and post-grasp manipulation in simulated dynamic environments, contributing to autonomous manipulation research.
[6]	Multi-cloud industrial data infrastructures	Addresses write-latency adaptation in geo-distributed multi-cloud replicas, a relevant problem for resilient industrial data management.
[7]	AI-driven decentralized manufacturing control	Develops theoretical foundations for decentralized AI-enabled manufacturing control and extends the discussion to future Industry 6.0 frameworks.
[8]	Machine learning for warehouse optimization	Uses machine learning to model and optimize warehouse performance, demonstrating interpretable data-driven decision support for logistics.
[9]	Smart IoT sensing for energy efficiency	Presents an IoT-based temperature-sensing device for glass-window monitoring, connecting industrial sensing, energy efficiency, and smart-building operation.
[10]	Secure software-defined industrial networks	Combines software-defined networking and AAS digital twins to address cybersecurity and resilience in industrial network infrastructures.

The robotics-oriented papers demonstrate the increasing importance of AI regarding perception and manipulation. Cloud-based vision services can reduce the barrier to implementing advanced visual recognition in robotic cells, but their deployment also raises questions about latency, robustness, data governance, and dependency on external infrastructures [2]. In parallel, deep reinforcement learning provides a route toward more adaptive robotic grasping and manipulation, especially in dynamic or uncertain environments, but still requires careful validation before transfer from simulation to production [5].

This direction is also consistent with recent work integrating trained deep learning vision systems with collaborative robots for real-time sorting and quality inspection [11]. Such contributions reinforce the need to evaluate AI-based perception not only through model-level metrics but also through deployment-oriented indicators such as cycle time, reliability, integration with robotic motion, and operational robustness.

The second group of papers addresses decentralized intelligence, digital twins, and industrial interoperability. The Asset Administration Shell is a key element for standardized industrial digital representations, but active and autonomous AAS implementations require mechanisms for negotiation, coordination, and decision-making. Multi-agent systems are therefore highly relevant for implementing AAS Type 3 functionalities [3]. This perspective is further extended by work on AI-driven decentralized manufacturing control and the use of AAS digital twins in secure software-defined industrial networks [7,10].

The third stream concerns data-driven industrial optimization and the infrastructures needed to support it. Machine learning can transform warehouse operation from rule-based management into predictive and optimization-oriented decision support [8]. However, such approaches depend on data infrastructures that can guarantee performance, consistency, and availability across distributed environments. The contribution on geo-distributed multi-cloud replicas therefore highlights an important enabling layer for future industrial platforms [6].

Finally, the Special Issue connects AI and control systems with sustainability and Industry 5.0 priorities. AI-driven transformations in manufacturing value chains can support predictive maintenance, resource efficiency, circular economy practices, and regulatory alignment [4]. Similarly, smart IoT sensing for energy-efficient monitoring shows how low-level sensing infrastructures can contribute to broader energy-management and sustainability objectives [9].

3. Knowledge Gaps and Open Challenges

Taken together, the papers indicate that AI and control systems are already producing practical results for industrial environments. Nevertheless, several gaps remain insufficiently sealed.

- **Trustworthy AI for closed-loop systems:** Industrial AI is increasingly used for perception, prediction, and optimization, but its integration into closed-loop control requires stronger evidence of robustness, explainability, safety, and performance under distribution shifts.
- **Interoperability between digital twins, AAS, and legacy systems:** Digital twins and AAS-based architectures are promising, but their implementation remains fragmented across platforms, communication protocols, semantic models, and organizational maturity levels.
- **Real-time edge-cloud and multi-cloud orchestration:** Industrial applications often require low latency, deterministic behavior, and high availability. These requirements are difficult to reconcile with cloud-based AI services and geographically distributed data infrastructures.

- **Cybersecurity and resilience in convergent OT/IT environments:** As industrial networks become software-defined, connected, and AI-enabled, the attack surface expands. Security must be designed as a system property rather than added after deployment.
- **Human-centricity beyond conceptual statements:** Industry 5.0 requires measurable integration of human factors, operator trust, ergonomics, skills, collaborative autonomy, and ethical decision-making. These dimensions are still less mature than purely technical optimization metrics. The educational and skills dimension is particularly relevant because AI-supported learning environments for electropneumatic control systems can help prepare engineers to design, diagnose, and maintain intelligent automation systems [12].
- **Sustainability-aware control and optimization:** Energy efficiency, circularity, and environmental impacts should become explicit objectives in AI-enabled industrial control rather than secondary evaluation criteria.
- **Reproducibility and benchmarking:** Many industrial AI studies remain difficult to reproduce because datasets, realistic benchmarks, deployment constraints, and long-term industrial validation protocols are limited.

4. Future Research Directions

Future research on AI and control systems for Industry 4.0 and 5.0 should move from isolated demonstrations to validated, interoperable, and human-compatible industrial ecosystems. The following priorities are particularly relevant.

- **Verifiable and explainable AI-enabled control:** New methods are required to combine machine learning with model-based control, formal verification, uncertainty quantification, and runtime monitoring. This is especially important for safety-critical robotic cells, adaptive production systems, and autonomous logistics.
- **Operational digital twins and AAS-based autonomy:** Digital twins should evolve from monitoring dashboards into operational entities capable of supporting diagnosis, negotiation, optimization, and autonomous or semi-autonomous control. Multi-agent systems can provide an architectural basis for this transition.
- **Edge-fog-cloud intelligence for industrial systems:** The next generation of industrial AI should distribute computation across sensors, controllers, edge nodes, fog layers, and cloud services according to latency, privacy, reliability, and cost constraints.
- **Cyber-resilient industrial networks:** Future industrial control infrastructures should integrate software-defined networking, zero-trust principles, attack modeling, anomaly detection, and digital-twin-based security assessment.
- **Human-in-the-loop and human-on-the-loop autonomy:** Industry 5.0 systems must support operators as active participants in decision-making. Research should address adaptive interfaces, explainable recommendations, skill augmentation, collaborative robotics, and measurable human-well-being outcomes.
- **Sustainability and circularity as control objectives:** AI-driven optimization should explicitly include energy consumption, emissions, material reuse, maintenance strategies, and circular economy indicators. This requires multi-objective control frameworks and life-cycle-aware decision support.
- **Industrial foundation models and agentic AI with safeguards:** Large AI models and autonomous software agents may support planning, troubleshooting, documentation, coding, and operator assistance, but their deployment in industrial environments requires domain grounding, verification, access control, and fail-safe integration.

- **Open benchmarks, datasets, and deployment evidence:** The field would benefit from shared datasets, simulation-to-real benchmarks, reference architectures, and longitudinal industrial case studies that report not only algorithmic accuracy but also downtime reduction, energy savings, productivity, safety, and maintenance impacts.

5. Conclusions

The Special Issue “Artificial Intelligence and Control Systems for Industry 4.0 and 5.0” reflects a field in rapid transition. AI is no longer limited to offline analytics; it is becoming embedded in robotic perception, industrial decision support, digital twins, control architectures, logistics systems, sensing devices, and cybersecurity mechanisms. At the same time, control systems are evolving from deterministic automation layers into adaptive and distributed infrastructures capable of interacting with data-driven intelligence.

The papers collected in this Special Issue demonstrate the breadth of this transformation. They also clarify that the success of AI-enabled industrial systems will depend not only on algorithmic performance but also on trustworthy deployment, interoperability, real-time behavior, cyber-resilience, sustainability, and meaningful human integration. These challenges define the research agenda for the next generation of Industry 4.0 and 5.0 systems and provide a strong foundation for future work at the intersection of artificial intelligence, control engineering, and industrial digital transformation.

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