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Cognitive Computing and Machine Intelligence in Fog-Cloud Infrastructure for Industry 5.0

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***Abstract*—In the context of Industry 5.0, the integration of cognitive computing and machine intelligence can significantly transform the industrial manufacturing processes. In the transition of Industry 4.0 to Industry 5.0, along with cognitive computing and machine intelligence, the integration of fog-cloud can further revolutionise future industries. This article briefly discusses the complex relationship among these technologies, with a specific focus on consumer devices. Subsequently, we design a decision-making system based on Deep Reinforcement Learning (DRL) within industrial environments. Finally, various issues and possible solutions in the context of cognitive computing and machine intelligence in Industry 5.0 are discussed.**

Introduction

Industry 5.0 signifies the most recent paradigm in the progression of industrial development, emphasising the harmonious collaboration between human workers and advanced technological systems. The current advancement in Industry 4.0 is possible because of the particular focus on the integration of human skills and the capabilities of intelligent systems. Subsequently, Industry 5.0 is expected to build upon the foundations laid by Industry 4.0 while introducing new concepts and technologies such as Artificial Intelligence (AI), Internet of Things (IoT), data analytics, and human-machine collaboration to bring evolution towards more intelligent, flexible, and sustainable manufacturing systems. This transition emphasizes production and supply chain processes tailored to individual needs while prioritizing sustainability and resilience. The fundamental components encompass human-machine

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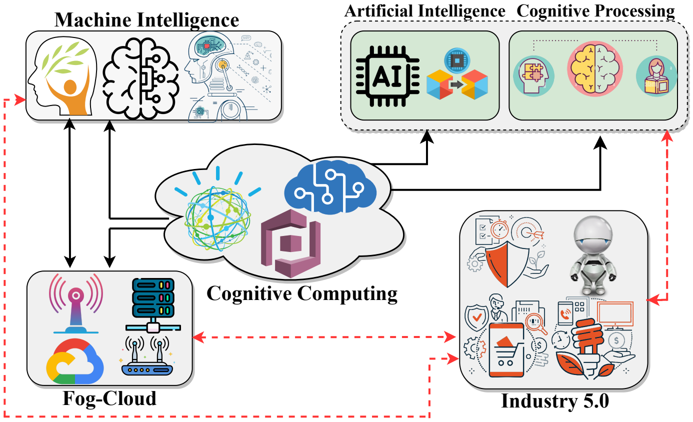

Figure 1: Cognitive computing and machine intelligence for Industry 5.0 using fog-cloud collaboration.

collaboration, cutting-edge technologies, and a holistic strategy for enhancing industrial operations.

Importance of Cognitive Computing and Machine Intelligence

Cognitive computing refers to the use of advanced AI systems that can simulate human thought processes to analyze complex data, understand natural language, and make informed decisions. In an industrial environment, various data and information, including sensors, production, maintenance, financial, and market data, are frequently fed into decision-making systems. With these data, cognitive computing enables machines to collaborate with humans in manufacturing processes by understanding context, learning from experiences, and continuously improving efficiency and productivity. Therefore, it can be expected that cognitive computing and machine intelligence will be integral components in consumer electronics and Industry 5.0, as illustrated in Fig. 1. These technologies are pivotal in advancing more intelligent and user-friendly products in consumer electronics. Machine intelligence, facilitated by Machine Learning (ML) methodologies, empowers devices to comprehend human preferences, anticipate requirements, and deliver tailored experiences. Cognitive computing introduces an additional dimension by integrating cognitive capabilities that resemble human brain processes [1]. This enables machines to make judgments aware of the surrounding context and adjust to evolving user needs.

In the context of Industry 5.0, cognitive systems can comprehend intricate data patterns, facilitating enhanced decision-making processes within the realms of manufacturing, supply chain management, and various other industrial sectors and their requirements such as for predictive maintenance, quality control, supply chain optimization, autonomous robotics, etc. Machine intelligence improves the flexibility of systems by acquiring knowledge from data and adapting to changing circumstances. Consequently, it can enhance operational effectiveness, decrease idle periods, and provide a more optimal allocation of resources.

Relevance of Fog-Cloud Infrastructure

Fog computing brings computing resources closer to the edge of the network, enabling real-time data processing and decision-making, whereas cloud computing provides enough storage and processing capabilities to support applications (e.g., UAV, supply chain management, mining, inventory management and robotics). The significance of Fog-Cloud infrastructure in the scope of Industry 5.0 is important. For example, the edge devices embedded within factory machinery collect real-time sensor data on equipment performance and environmental conditions. This data is then processed locally at the edge (fog computing) to identify anomalies or inefficiencies, such as machine malfunctions or suboptimal operating parameters. Critical insights from this edge data processing are transmitted to the cloud for further analysis, enhancing overall operational efficiency and minimizing downtime. Thus, fog-cloud Infrastructure is well-suited to meet the demands (both computing and quick response) of Industry 5.0.

Within the context of Industry 5.0, Fog-Cloud infrastructure can enable prompt decision-making, adaptability, and intelligent automation [2]. It can further enhance the processing and analysis of data at the edge

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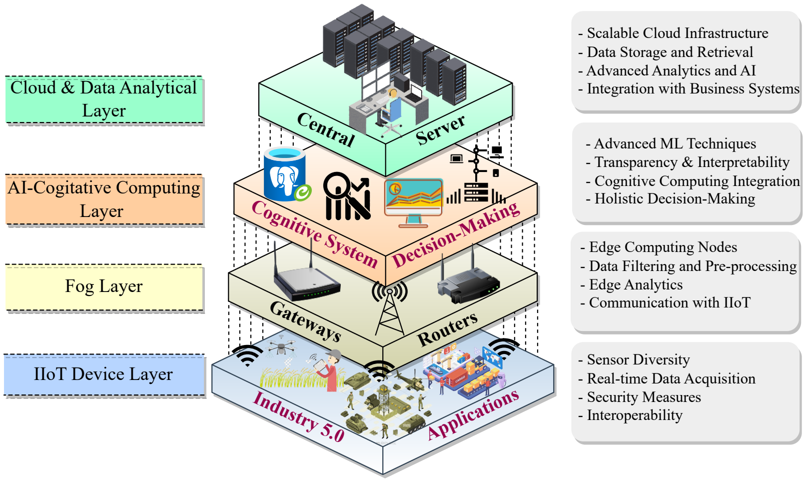

Figure 2: High-level architecture of Fog-Cloud integration in Industry 5.0.

of the network, closer to the origin of data generation. Implementing this approach shows a notable decrease in latency, guaranteeing prompt and timely reactions to dynamic situations in the industrial sector. The Fog layer, located at the periphery, performs data pre-processing, filtering, and initial analytics before transmitting pertinent information to the Cloud layer for further comprehensive analysis.

Additionally, utilising Fog-Cloud infrastructure is of utmost importance in facilitating the substantial volume of data produced by the devices of the Industrial Internet of Things (IIoT) in Industry 5.0. A distributed architecture guarantees data storage, processing, and management optimisation, facilitating the smooth incorporation of advanced technologies such as cognitive computing and machine intelligence [3]. Therefore, the Fog-Cloud infrastructure along with IIoT can significantly enhance their capacities to establish a highly adaptable, expandable, and intelligent framework that supports the requirements of Industry 5.0.

Evolution and Foundations

Transition from Industry 4.0 to Industry 5.0

The shift from Industry 4.0 to Industry 5.0 signifies a notable transformation in industrial systems. Industry 4.0 established the foundation for the digitization of manufacturing operations by incorporating intelligent technologies [4]. In contrast, Industry 5.0 advances this progression by emphasising the cooperative interaction between humans and machines, promoting harmonious collaboration. The primary emphasis of Industry 4.0 was on integrating automation, data interchange, and adopting the IIoT to optimize operational efficiency. Nevertheless, Industry 5.0 brings about a fundamental change by emphasizing the crucial significance of human participation in industrial operations. The core objective of Industry 5.0 is to establish a harmonious ecosystem in which advanced technologies, such as cognitive computing and machine intelligence, work in conjunction with human skills to foster innovation, individualization, and environmental responsibility.

Fog-Cloud Integration in Industry 5.0

Essential Concepts of Cognitive Computing and Machine Intelligence

The key principles of cognitive computing and machine intelligence are the foundation for revolutionary technologies reconfiguring industrial environments. Cognitive computing, drawing inspiration from the human brain's cognitive processes, encompasses developing systems that can learn and adapt, enabling them to grasp information, engage in reasoning, and ultimately make informed judgments. This field comprises multiple elements, including NLP, pattern recognition, and algorithms that can learn autonomously. Conversely, machine intelligence pertains to the advancement of algorithms and models that empower computers to execute jobs necessitating intellect resembling humans. This pertains to ML, wherein systems acquire knowledge from data and enhance their performance through iterative processes. Collectively, these concepts enable industrial systems to analyze intricate data, extract significant insights, and independently make well-informed judgments. Within Industry 5.0, integrat-

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ing cognitive computing and machine intelligence is crucial, facilitating a mutually beneficial association between human operators and intelligent systems to augment productivity, creativity, and problem-solving capacities inside industrial environments.

Architecture

The integration of Fog-Cloud in Industry 5.0 can also be easily connected with IoT devices available in smart industries for better and real-time data collection and actuation. The architecture depicted in Figure 2 consists of multiple layers, each playing a unique role in enhancing the overall intelligence and productivity of the industrial ecosystem. The complete architecture is discussed as follows.

1) **IIoT Device Layer:** The foundation of fog-cloud integration for Industry 5.0 is the IIoT Device Level. Herein, integrating sensors and actuators into devices makes it possible to gather real-time data and execute physical actions in response to the collected data, effectively bridging the gap between the digital and physical worlds, enabling real-time monitoring and analysis to optimize operations and drive innovation in Industry 5.0.

2) **Fog Layer:** This layer is also popularly termed as the *Edge layer*, where the data obtained from IIoT devices undergoes preliminary processing. The key components within this level are fog devices, which are strategically placed near IIoT devices and include gateways and fog servers. Fog computing nodes carry out real-time analytics on the data, thereby decreasing the amount of information that needs to be transmitted to the cloud. This level offers faster response times and reduces bandwidth requirements, making it suitable for applications requiring immediate response.

3) **AI-Cognitive Computing Layer:** This layer incorporates cutting-edge ML strategies, such as reinforcement learning and DRL, to enable autonomous adjustment and enhancement of manufacturing procedures. This layer emphasizes transparency and comprehensibility in decision-making. Cognitive computing employs self-learning algorithms, data mining, pattern recognition, and NLP to mimic and comprehend human thought processes. Collectively, these elements form a comprehensive AI-cognitive computing Layer, promoting better and more informed decision-making in the cognitive factory.

4) **Cloud Layer:** The highest layer of the architecture integrates essential components, such as Cloud Services, which provide scalable storage, computational resources, and services optimized for managing large volumes of data. Data that cannot be processed in real-time or at the fog layer is sent to this layer. Advanced Big Data Analytics tools process massive datasets, extracting critical insights for strategic decision-making. This is supported by robust Data Storage solutions, enabling efficient archiving and retrieval of historical data, resulting in a comprehensive and effective data management approach.

Performance Analysis

Our simulation considers a range of parameters, including 10–100 IIoT devices, 5–10 fog devices, 4 service requests per IIoT device, and three cloud servers. Additionally, we set transmission bandwidth to 130 MHz, task size 5-20 Kb, and a processing density of 1900 [cycles/second] for IIoT devices. Furthermore, we specify maximum CPU frequencies for IIoT devices, fog devices, and cloud servers as 500×10^6 $[cycle/second]$, 50×10^9 $[cycle/second]$, 100×10^6 $[cycle/second]$, respectively, with transmission energy 1.42×10^{-7} J/bit.

The DRL technique utilizes a mini-batch training method and considers a batch size 32, a learning rate of 0.0001, 10000 epochs, and a replay memory size 2000. A Deep Neural Network (DNN) is structured with a single input layer, three hidden layers, and one output layer. We also illustrate overall system cost and rewards in Fig. 3 and Fig. 4. To evaluate the variability of reward values among industrial networks, a range of network optimizers, including Adamax, SGD, and RMSprop, are employed for testing purposes. The efficacy of the suggested DRL method in decision-making, after iterations and learning from prior experiences, is demonstrated by its superior performance in optimizing the overall system cost compared to the random action strategy.

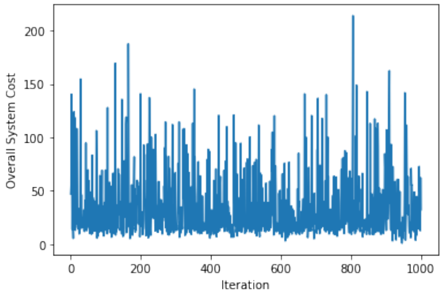

Figure 3: Performance analysis of overall system cost.

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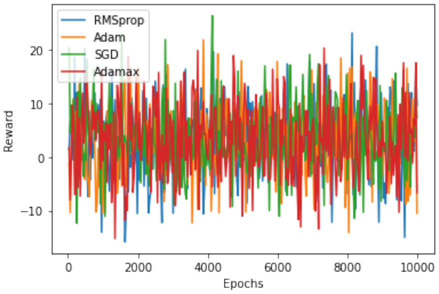

Figure 4: Performance analysis of system reward.

Challenges and Future Directions

Security and Privacy in Cognitive Computing

In Industry 5.0, where cognitive computing and machine intelligence are significant factors, protecting sensitive data's security and privacy is critical. Incorporating these technologies into the Fog-Cloud infrastructure gives rise to apprehensions regarding illegal entry and the possibility of data breaches [5]. To address these issues, it is crucial to prioritize the deployment of resilient encryption techniques, secure protocols for data transfer, and comprehensive methods for access control. Moreover, implementing privacy-preserving methodologies, such as federated learning, can provide collaborative model training while safeguarding sensitive data from being exposed to the cloud, thereby augmenting data security.

Scalability in Fog-Cloud Integration

Scalability holds significant importance when deploying Fog-Cloud infrastructure for Industry 5.0. With the exponential growth in data volume, conventional architectures may encounter difficulties in managing the heightened workload [6]. To tackle this issue, fog computing technologies for localized data processing might mitigate the strain on cloud infrastructure, facilitating efficient and scalable operations. Incorporating adaptive resource allocation methods and fog caching technologies can enhance system performance, facilitating smooth integration into Industry 5.0 contexts.

Interoperability in Consumer Electronics

The wide range of consumer electronics products in Industry 5.0 requires a significant compatibility layer. Establishing smooth communication and efficient data sharing among diverse devices is paramount for the effective functioning and triumph of cognitive computing and machine intelligence applications [7]. The promotion of interoperability is facilitated by using standardized communication protocols, such as Message Queuing Telemetry Transport (MQTT) or Constrained Application Protocol (CoAP). Furthermore, advancing middleware solutions will enable the compatibility of various devices, and the standardization of data formats will enhance the efficiency of interactions in the Industry 5.0 ecosystem.

Ethical Implications of Machine Intelligence

The ethical challenges associated with machine intelligence, particularly in AI, are numerous and varied. Such issues include potential biases in algorithms that may result from skewed data or inherent prejudices, as well as the need for transparent and fair ethical frameworks in the development process. Examples of biases in AI algorithms, such as gender bias in recruitment tools or racist content generated by AI-powered tweets, highlight the importance of comprehensive reviews and balanced training data. Ethical frameworks, such as the AI4People principles (beneficence, non-maleficence, autonomy, justice, and explicability), play a crucial role in ensuring accountability and the implementation of human-centric AI [8].

Rapid Technological Changes

The rapid and dynamic progression of technology is a formidable obstacle in the preservation of the pertinence and adaptability of cognitive computing and machine intelligence solutions such as federated learning, distributed ML or Quantum ML. Adopting an agile development methodology and implementing modular architectures facilitate rapid adjustment to evolving technology. The implementation of ongoing surveillance of technical advancements and the cultivation of partnerships with research institutions can facilitate the maintenance of up-to-date knowledge regarding state-of-the-art progressions. Implementing novel frameworks that can provide seamless upgrades would be crucial for maintaining the adaptability of Fog-Cloud infrastructure in the dynamic context of Industry 5.0.

Conclusion

This article explored the profound effects of incorporating cognitive computing and machine intelligence into Industry 5.0. It presented an empirical study on the effectiveness of adopting a DRL-based decision-making system in industrial settings while also addressing the transition from Industry 4.0 to Industry

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5.0. Considering the current epoch of industrial transformation, we provided a detailed discussion on effective solutions for security, scalability, interoperability, and integration of rapid technological advancements in dynamic environments for the advancement of Industry 5.0, with a particular emphasis on the impact of cognitive computing.

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