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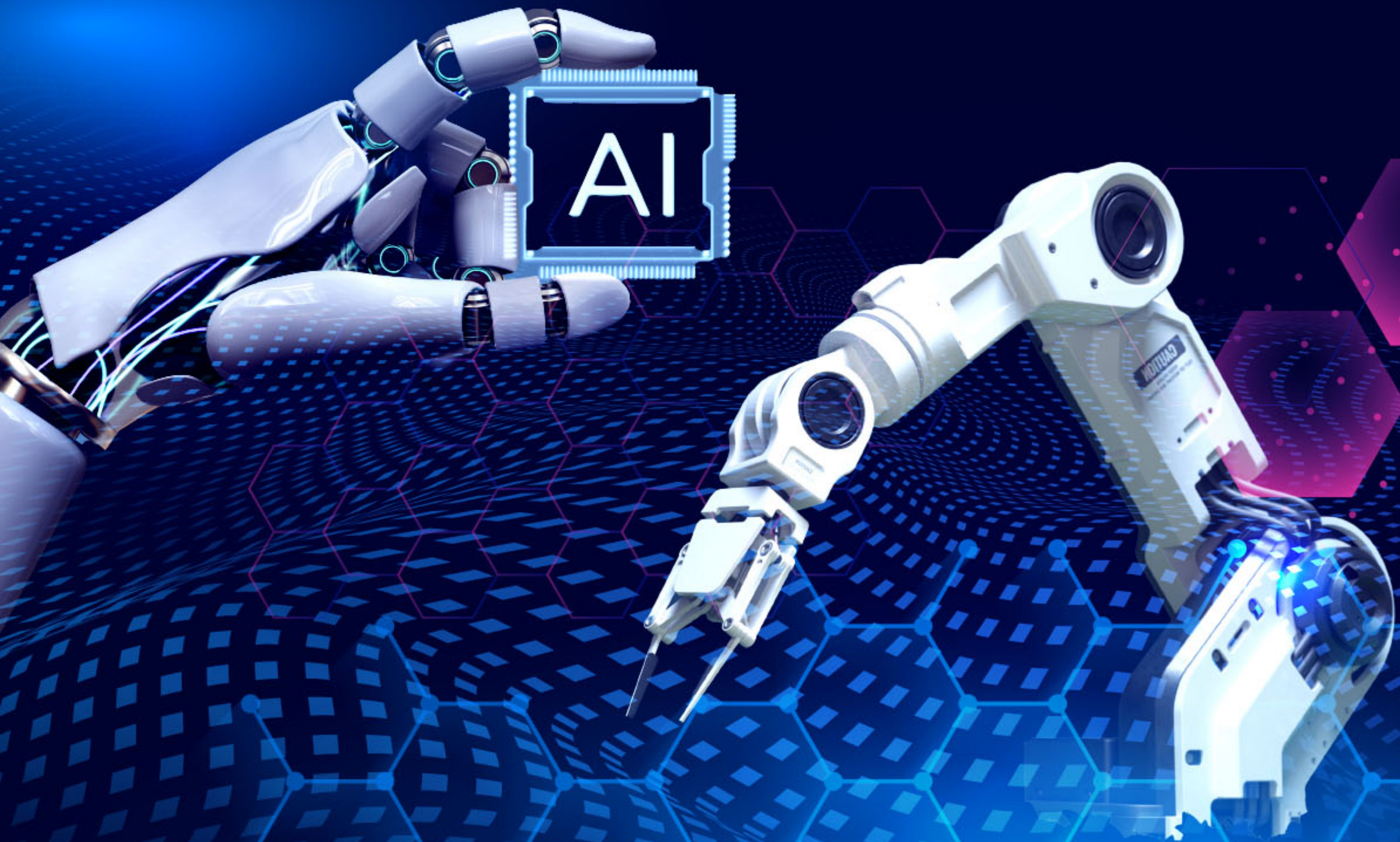
透過工業人工智能

賦能企業走向先進製造



1 何為工業人工智能

1.1 工業人工智能發展歷程

從20世紀以電氣化和資訊化為代表產生的工業革命以來，製造業賴以賦能的主要途徑是自動化生產線，透過傳感器和工控設備，實現基本的數據收集和自動控制，從而提升生產效率和產品 質量的穩定性。然而，隨著技術的不斷反複運算，製造企業面臨的機會和挑戰並存，市場環境變化越來越快。尤其近年來，隨著大數據、雲端運算和物聯網等先進技術的應用，使得生產線上的設備和系統能夠互聯互通，進一步實現了更高層次的智慧控制和協同作業，推動製造業進入了新的階段。

為了適應工業環境的不斷變化，提升企業的洞察力，並最終實現生產效率或產品性能的提升，具有自我感知、自我學習、自我執行、自我決策和自我調整的能力的AI技術為製造業提供了新的動力。工業人工智慧簡稱為工業AI，是一種將AI科技與製造業應用場景融合的技術，以實現設計模式的創新、生產系統的智慧決策和資源的優化配置等[1]。近年來AI技術創新不斷湧現，更多的製造企業正在將這些技術融入工業場景的各個環節，以實現從生產到服務的全流程智慧化。在未來，隨著AI技術的進一步發展和數據的不斷積累，我們可以確信，工業AI在食品、電子、服裝、醫療、保潔等製造業各個領域會得到越來越廣泛的應用，為企業提升效率、減少成本、提高產品品質等方面提供巨大的可能性和機會。

1.2 工業人工智能與新質生產力

AI 創新正成為技術創新和應用整合的關鍵，全球主要製造業強國都已將工業 AI 做為國家政策的重點。美國將工業 AI 納入其國家戰略的關鍵和新興技術，充分利用其在AI領域的優勢，賦能先進製造等領域，引領未來的產業發展。歐盟將工業 AI 納入其 2030 年的數字羅盤戰略，提出在 2030 年實現 75% 的歐盟企業使用雲端計算、大數據和人工智慧的目標。日本將工業 AI 納入其第六期科技創新基本計劃，以 AI 技術為基礎，構建了智慧時代「5.0社會」的未來藍圖。韓國基於數字的產業創新發展策略積極推動各行業應用 AI 來實現產品設計和研發、製造工藝創新、新型智慧產品和新概念服務等[2]。

我國在製造業領域擁有健全的產業鏈、龐大的規模和不同類型的應用場景，因此在發展工業人工智慧方面具有廣範需求和天然優勢，2002年，中國共產黨第十六次全國代表大會首次提出「新型工業化」的概念，之後二十多年來，一直作為我國發展製造業的重要指導策略。新型工業化以知識化、資訊化、全球化、生態化作為其本質特徵，堅持以科技變革為引領，推動傳統產業改造升級、培育戰略性新興產業。2023年9月，國家主席習近平在黑龍江省考察調研期間首次提到“新質生產力”，面對新一輪科技革命和產業變革帶來的發展機遇與挑戰，進一步明確了新型工業化的發展重點和方向，2024年3月，發展新質生產力被寫入兩會政府工作報告，以積極培育新能源、新材料、先進製造、電子資訊等戰略性新興產業和未來產業，增強發展新動能。

早在2018年，國家就明確支持將香港建設成為國際創新科技中心，在2022年發布的《香港創新科技發展藍圖》中[3]，香港特區政府確定了四大科創發展方向：優化創科 生態系統，推動香港的「新工業化」；擴大創科人才庫，提升發展潛力；推進數字經濟的發展，打造智慧香港；積極參與國家的發展大局，成為連接內地和世界的重要橋樑。在推進科技創新產業的過程中，香港不僅積極吸引企業和人才，還致力於推動「再工業化」。具體措施包括建立先進製造中心，利用創新科技推動製造業的升級轉型；計劃在香港增設更多的智慧生產線；加強與香港生產力促進局的合作，幫助企業實現智慧製造。

1.3 工業人工智能定義

工業AI與傳統AI的區別在於，前者是一種更為嚴謹的系統科學，面向各類工業場景開發、驗證和部署機器學習演算法，並實現持久、可靠、安全的運作。根據美國辛辛那提大學李傑教授的定義[1]，工業AI的技術要素包括數據技術（data technology，DT）、分析技術（analytic technology，AT）、平台技術（platform technology，PT）、操作技術（operation technology，OT）和人機互動技術（human-machine technology，HT）。這些要素共同構成了一個以分析技術為核心的框架，我們稱之為資訊物理系統（Cyber-Physical System，CPS），該框架處理工業場景中收集的大數據產生的信息，結合領域的專業知識作為分析判斷的標準，以協助製造商做出決策，最後再使用驗證工具修正模型，使其更可靠並確保其時效性。

1.3.1 工業人工智能技術要素

1.3.1.1 數據技術

工業場景下收集所得的原始數據普遍存在碎片化、質量低和噪音等問題，數據技術屬於資訊物理系統架構中的智慧感知層，目標是解決獲取原始數據後的預處理問題。透過數據技術，系統可以對不同來源的數據進行統一收集，並實現有效數據的自動提取，用於提高建模數據的標準化程度。在預處理數據時，需要解決數據同步問題。

1.3.1.2 分析技術

分析技術在工業AI系統中扮演著核心角色，該技術將智慧演算法、領域專家知識和數據結合和訓練並得到的可部署模型。分析技術在資訊物理系統架構中屬於智慧分析層，依照模型部署的具體位置，可劃分為邊緣端分析與雲分析。其中，邊緣端靠近工業現場，使得邊緣端分析能夠得到較好的實時性，但由於邊緣端的數據處理速度和存儲能力有限，因此，當模型較複雜或參數較大時，邊緣端難以實現集中式 的模型訓練和運行。 對於雲端分析，需要基於統一的分析管理系統，綜合考慮不同領域、不同系統的多源數據融合分析。另外，以工業應用的智慧演算法，在進行建模分析時需要充分考慮小樣本資料的特性，採用如半監督學習、自我調整學習或遷移學習等適用性強的方法。

1.3.1.3 平臺技術

平臺技術主要包括邊緣端平臺、雲端平臺以及平臺間的互動網絡，在資訊實體系統架構中，平臺技術支援從智慧感知層、智慧分析層到網路連接層的功能。對於邊緣端運算平臺，平臺技術可透過底層硬體創新或升級來提升資料收集和處理能力，以及實現不同平臺之間的協同作業。對於雲端平臺，平臺技術透過建構模型全生命週期管理的基礎軟硬體系統，進行工業應用場景下的不確定性管理和AI演算法的持續優化。此外，隨著邊緣端平臺之間、邊緣端與雲端平臺之間的深度互聯，網路德安全性問題也越來越受到重視。

1.3.1.4 運營技術

運營技術研究如何將模型的預測結果有效地應用於管理決策，從而實現生產和運維模式從傳統的經驗驅動到數據驅動的變革。運營技術的流程優化是在資訊物理系統架構中的智慧認知層完成的。

1.3.1.5 交互技術

工業AI的應用同時帶來了人與製造系統互動方式的變革，由於未來工廠處理的數據量大幅提升，新型的人機交互方式將能夠協助生產者高效和直觀的獲取最有價值的信息，從而讓工業AI科技更好地融入生產製造，賦能生產製造。近年來，智慧互動技術在工業應用場景中廣範應用，如語音識別系統，動作捕捉，虛擬現實/增強現實（VR/AR），數字孿生技術等。人機互動技術在資訊物理系統架構中處於智慧執行層。

1.3.2 工業人工智能系統架構

如上一節所討論，工業AI的技術元素透過資訊物理系統的架構被整合在一起，並在不同層次上發揮各自的功能。資訊物理系統架構的概念是李傑教授在《CPS：新一代工業AI》一書中首次提出的[4]，並將其簡稱為5C架構，5C分別代表智慧感知層（Connection）、智慧分析層 （Conversion）、網絡層（Cyber）、智能認知層（Cognition）、智能決策與執行層（Configuration）。資訊物理系統5C架構是將工業AI的5T元素整合的核心框架，也是工業AI實現其閉環控制的功能架構。

1.3.2.1 智慧感知層

作為分佈於底層的支援系統，智慧感知層主要由傳感器網絡和數據採集系統組成。根據應用場景需求和分析目標，智慧感知層可以對重要的資料進行選擇性收集。在智慧感知層，需要根據資料類型和分佈確定收集方法和管理策略，對並收集的資料進行必要的過濾和預處理，以保證資料的品質和完整性，為上層應用提供資料支持。

1.3.2.2 智能分析層

智能分析層通過對數據進行特徵提取、篩選、分類和優先順序排列等處理，提高數據的可解讀性，最終將將低價值密度的信息轉化為高價值密度的信息。在智能分析層，我們會用到用於數據處理的各類方法，例如，采用捲積神經網絡（CNN）對采集的圖像數據進行特徵提取，采用模式識別對振動信號進行分類。

1.3.2.3 網絡連接層

網絡連接層通過搭建網絡綫路來對工業場景中的多源信息進行整合，并在網絡信息空間中創建能夠指導真實場景的模擬環境，進而將人機料法環等生產要素有機地融合。同時，在網絡連接層中，應實現數據同步、信息關聯、變動記錄等功能。

1.3.2.4 智能認知層

智能認知層根據工業場景下的需求，結合先驗知識對多源數據進行動態連結和評價分析，不斷反覆運算優化對物理系統運作規則的理解，以及對生產要素間的連結、影響分析與預測，逐步建立和完善主動認知能力。在複雜的工業應用場景下，需全面的評估各類不確定性因素，以保証模型的預測結果能夠有效地應用於管理決策。

1.3.2.5 智能執行層

為了將模型的分析結果更好的用來輔助運營決策，並將其有效同步到執行系統，須確保信息的時效性和系統間的協同。工業AI技術賦能製造的關鍵在於它可以將強大的數據處理能力與工業製造場景有機整合為一體，從而突破傳統生產系統在時間和空間上的限制。相應的，信息世界和物理世界之間的交互方式的變革，有助於我們快速找到最具價值的要素，進而形成一個高效的閉環優化過程，實現持續改進。

1.3.3 工業人工智能與通用人工智能的區別

通用人工智能（General Artificial Intelligence）作為一種認知學科，近年來發展迅猛，已經在多個領域得到了廣範的應用，例如機器學習、模式識別、自然語言處理、計算機視覺、機器人技術等。然而，由於缺乏嚴格的數學模型支撐，通用人工智能算法得到的結果大多被視為一種概率事件，並且常常被認為缺乏嚴謹。工業場景下的核心需求在於穩定性、標準化、精確性和可重複性，以及與機械設備、工藝和生產流程的緊密結合。因此，在人工智能技術能夠完全融入工業系統之前，首先必須要解決可重複性、可靠性和安全性等問題。工業人工智能是系統科學，專注於針對工業場景開發、驗證和部署算法，以實現系統在應用環境中可持續的、安全的、可靠的運行。工業人工智能目前在設備維護、視覺檢測、品質追蹤、生產排程、物料周轉和能效優化等工業製造相關領域已經得到了集中應用。

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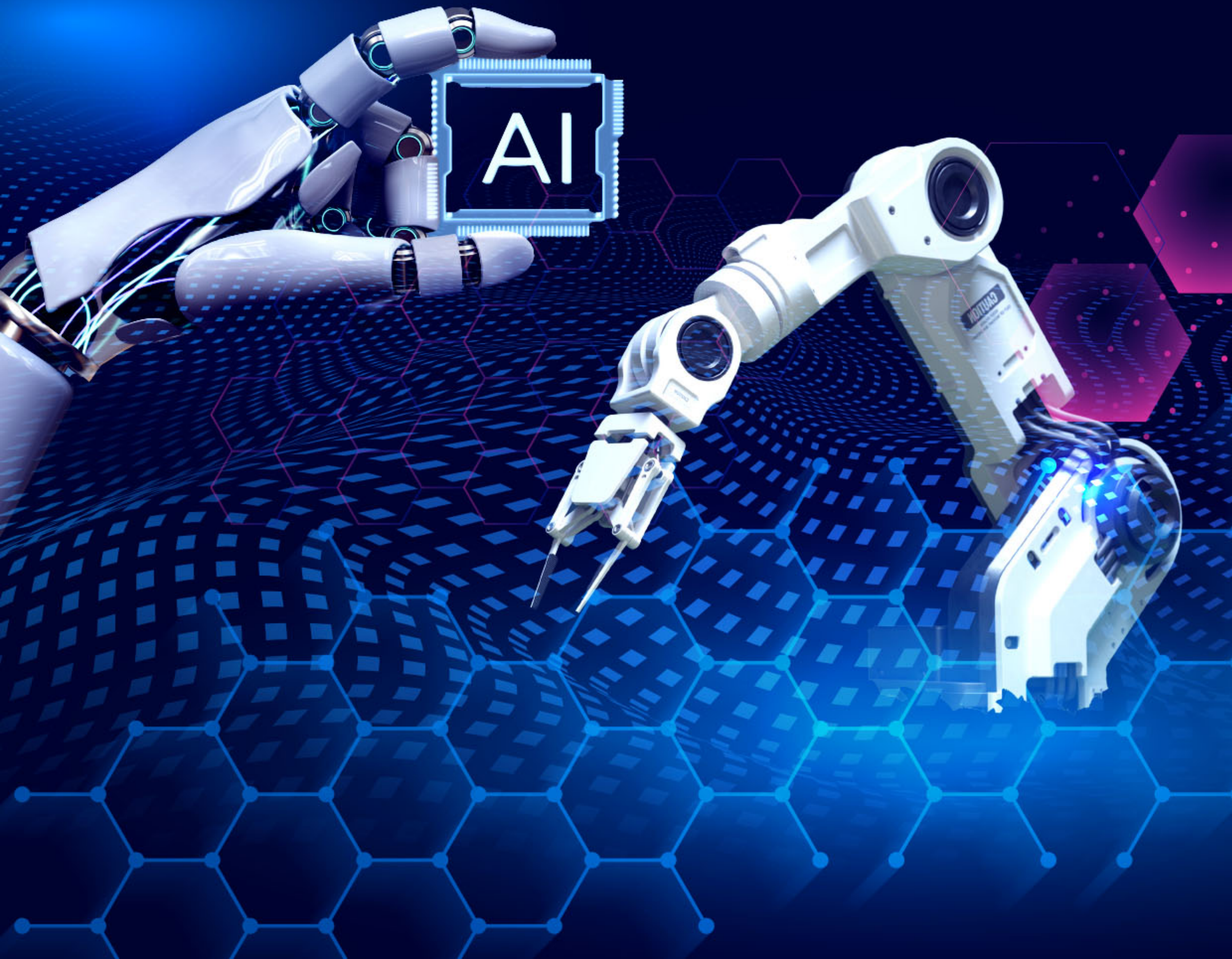
Unlocking The Potential Of Industrial AI To Advanced Manufacturing



1 What is Industrial Artificial intelligence

1.1 Development History of Industrial Artificial Intelligence

Since the industrial revolution represented by electrification and informatization in the 20th century, the main way for manufacturing enterprises to improve their production ability has been through automated production lines. Through sensors and industrial control equipment, basic data collection and automatic control are achieved, thereby improving production efficiency and product quality stability. However, with the continuous upgrading of technology, manufacturing enterprises are facing both opportunities and challenges, as a result of that the market environment is changing rapidly. Especially in recent years, with the application of advanced technologies such as big data, cloud computing, and the Internet of Things, equipment and systems on production lines can be interconnected, further achieving higher-level intelligent control and collaborative operations, thus driving the manufacturing industry into a new stage.

In terms of meeting the need of the rapidly changing industrial scenarios, enhancing the insight of enterprises, and ultimately achieving the improvement of production efficiency or product performance, AI technology with the ability of self perception, self-learning, self execution, self decision-making, and self adjustment provides new impetus for the manufacturing industry. Industrial artificial intelligence, abbreviated as industrial AI, is a technology that integrates AI technology with manufacturing application scenarios to creat innovation in design patterns, intelligent decision-making in production systems, and optimization of resource allocation[1]. In recent years, AI technology innovation has emerged continuously, and more manufacturing enterprises are integrating these technologies into various aspects of industrial scenarios to achieve intelligence from production to service. In the future, with the further development of AI technology and the continuous accumulation of data from industrial scenarios, we can be confident that industrial AI will be increasingly widely used in various manufacturing fields such as food, electronics, clothing, medical, and cleaning products, providing huge possibilities and opportunities for enterprises to improve efficiency and product quality, as well as reduce costs.

1.2 Industrial Artificial Intelligence and New Quality Productivity

AI innovation is becoming the key to technological innovation and application integration, and major manufacturing powers around the world have made industrial AI a focus of national policies. The United States has included industrial AI as a key emerging technology in its national strategy, fully utilizing its advantages in the field of AI, to empower advanced manufacturing and other fields, and lead future industrial development. The EU has incorporated industrial AI into its 2030 digital compass strategy, aiming to make 75% of EU enterprises to utilize cloud computing, big data, and artificial intelligence by 2030. Japan has included industrial AI in its sixth basic plan for technological innovation. Based on AI technology, japan has estabilshed a future blueprint for the "5.0 society" in the intelligent era. South Korea's digital based industrial innovation development strategy actively promotes the application of AI in various industries to achieve product design, development, and manufacturing process innovation, as well as new intelligent products, and noval services[2].

In terms of intelligent manufacturing, China has a sound industrial chain, huge scale and different types of application scenarios, so it has a wide range of needs and natural advantages in the development of industrial artificial intelligence. In 2002, the 16th National Congress of the CPC first proposed the concept of "new industrialization", which has been an important guiding strategy for the development of China's manufacturing industry for more than 20 years. The essential characteristics of new industrialization are knowledge-based, information-based, globalized, and ecological. It adheres to the guidance of technological revolution, promotes the transformation and upgrading of traditional industries, and cultivates strategic emerging industries. In September 2023, President Xi Jinping proposed "new quality productivity" for the first time during a pilot study in Heilongjiang Province. Facing the development opportunities and challenges brought by the new technological revolution and industrial transformation, the new quality productivity further clarifies the development focus and direction of new industrialization. In March 2024, the new quality productivity was included in the government work report of the China's Two Sessions, aim to actively cultivate strategic emerging industries and future industries such as new energy, new materials, advanced manufacturing, and electronic information.

Early from 2018, the Chinese central government has explicitly supported Hong Kong as an international innovation and technology center. In the "Hong Kong Innovation and Technology Development Blueprint"[3] released in 2022, the Hong Kong Special Administrative Region government identified four major directions for the development of innovation and technology: optimizing the innovation and technology ecosystem to promot Hong Kong's "new industrialization"; expanding the pool of innovative talents to enhance development potential; promoting the development of the digital economy to build a smart Hong Kong; actively participating in the national development agenda to become a vital bridge connecting the mainland and the world. In the process of promoting technology innovation industries, Hong Kong is actively attracting enterprises and talents while also focusing on promoting "reindustrialization". Specific measures include establishing advanced manufacturing centers and utilizing innovative technology to promote the upgrading and transformation of the manufacturing industry. Plans are also in place to increase the number of intelligent production lines in Hong Kong. Collaboration with the Hong Kong Productivity Council is being strengthened to assist companies in achieving intelligent manufacturing.

1.3 Definition of Industrial Artificial Intelligence

The difference between industrial AI and traditional AI is that the former is a more rigorous system science. The industrial AI focuses on developing, validating, and deploying machine learning algorithms for various industrial scenarios, aiming to achieve persistent, reliable, and secure operations. According to Professor Jie Li from the University of Cincinnati in the United States, the technical elements of industrial AI include data technology (DT), analytical technology (AT), platform technology (PT), operation technology (OT), and human-machine technology (HT). These elements together form a framework centered around analytical techniques, known as Cyber Physical System (CPS), which processes information generated by big data collected from industrial scenarios, combines expert knowledge as a standard for analysis and judgment, assists manufacturers in making decisions, and finally uses validation tools to modify the model to ensure its reliability and timeliness.

1.3.1 Elements of Industrial Artificial Intelligence Technology

1.3.1.1 Data technology

The raw data collected in industrial scenarios generally suffers from fragmentation, low quality, and noise. Data technology belongs to the connection layer in the architecture of cyber-physical systems, with the goal of solving the preprocessing problem after obtaining raw data. Through data technology, the system can collect data from different sources in a unified manner and achieve automatic extraction of valuable information to improve the standardization of modeling data. When preprocessing data, it is necessary to solve the problem of data synchronization.

1.3.1.2 Analytical technology

Analysis technology plays a crucial role in industrial AI systems, which combines intelligent algorithms, expert knowledge, and data to train deployable models. In the architecture of cyber-physical systems, analysis technology belongs to the conversion layer and can be divided into edge analysis and cloud analysis based on the specific deployment location of the models. Edge analysis is close to the industrial site, allowing for better real-time performance. However, due to the limited data processing speed and storage capacity at the edge, it is difficult to achieve centralized model training and operation when dealing with complex models or large parameters. For cloud analysis, it is necessary to establish a unified analysis management system and comprehensively consider multi-source data fusion analysis from different domains and systems. Additionally, intelligent algorithms for industrial applications need to fully consider the characteristics of small sample data during modeling and analysis. Methods such as semi-supervised learning, self-adjusting learning, or transfer learning, which are suitable for such scenarios, should be employed.

1.3.1.3 Platform technology

Platform technology mainly includes edge platforms, cloud platforms, and interaction network between platforms. In the architecture of cyber-physical systems, platform technology supports the functions of connection layer, conversion layer and cyber layer. For edge platforms, platform technology can improve data collection and processing capabilities through underlying hardware innovation or upgrades, as well as achieve collaborative operations among different platforms. For cloud platforms, platform technology builds a basic software

and hardware system for model lifecycle management, enabling uncertainty management in industrial application scenarios and continuous optimization of AI algorithms. In addition, with the deep interconnection between edge platforms and between edge and cloud platforms, network security issues are also receiving increasing attention.

1.3.1.4 Operation technology

Operation technology research focuses on effectively applying the predictive results of models to management decisions, thereby achieving a transformation of production and operation modes from traditional experience-driven to data-driven approaches. The process optimization of operational technology is completed in the cognition layer of the cyber-physical system architecture.

1.3.1.5 Human-machine technology

The application of industrial AI has brought about a transformation in the way people interact with manufacturing systems. With the significant increase in the amount of data processed by factories in the future, a new approach to human-machine interaction will assist producers in efficiently and intuitively accessing the most valuable information and thus enable industrial AI technology to better integrate into production and empower manufacturing. In recent years, intelligent interaction technology has been widely applied in industrial scenarios, such as speech recognition systems, motion capture, virtual reality/augmented reality (VR/AR), digital twin technology, etc. Human-machine technology is located at the configuration layer in the cyber-physical systems architecture.

1.3.2 Architecture of Industrial Artificial Intelligence System

As discussed in the previous section, the technological elements of industrial AI are integrated together through the architecture of cyber-physical systems (CPS) and perform their functions respectively at different levels. The concept of CPS architecture was first proposed by Professor Li Jie in the book "CPS: The New Generation of Industrial AI" [4], and it is abbreviated as the 5C architecture. The 5C represents the Connection layer, Conversion layer, Cyber layer, Recognition layer, and Configuration layer. The 5C architecture of information physics systems is the core framework that integrates the 5T elements of industrial AI, and it is also the functional framework for industrial AI to achieve its closed-loop control.

1.3.2.1 Connection layer

As a supportive system deployed on the bottom level, the connection layer is mainly composed of sensor networks and data acquisition systems. According to the application scenario requirements and analysis objectives, the perception layer can selectively collect important data. In the intelligent perception layer, it is necessary to determine the collection method and management strategy based on data type and distribution. The collected data should undergo necessary filtering and preprocessing to ensure data quality and integrity, providing data support for upper-layer applications.

1.3.2.2 Conversion layer

The conversion layer improves the interpretability of data by performing tasks such as feature extraction, filtering, classification, and prioritization, ultimately transforming low-value density information into high-value density information. Various methods for data processing are employed in the analytics layer, such as using convolutional neural networks (CNN) to extract features from collected images and using pattern recognition to classify vibration signals.

1.3.2.3 Cyber layer

The cyber layer integrates multi-source information in industrial scenarios by building network circuits and creates a simulation environment in the cyberspace that can guide real scenarios, enabling the organic integration of production factors including human, machine, material, method, and environment. Additionally the functions such as data synchronization, information association, and change recording should be implemented in the connectivity layer.

1.3.2.4 Recognition layer

The cognition layer combines prior knowledge to dynamically connect and evaluate multi-source data based on the needs of industrial scenarios. It continuously iterates to optimize the understanding of physical system operation rules, as well as the analysis, prediction, and connections between production factors. This gradual process establishes and improves proactive cognitive capabilities. In complex industrial application scenarios, it is essential to comprehensively

evaluate various uncertainties to ensure that the prediction results of the model can be effectively applied in management decision-making.

1.3.2.5 Configuration layer

To effectively utilize the analysis results of the model to assist operational decision-making and synchronize them with the execution system, it is necessary to ensure the timeliness of information and the coordination between systems. The key to empowering manufacturing with industrial AI technology lies in its ability to organically integrate powerful data processing capabilities with industrial manufacturing scenarios, thereby breaking through the limitations of traditional production systems in terms of time and space. Correspondingly, the transformation of the interaction between the information world and the physical world helps us quickly identify the most valuable elements, leading to an efficient closed-loop optimization process and achieving continuous improvement.

1.3.3 Differences between Industrial AI and General AI

General Artificial Intelligence, as a cognitive discipline, has developed rapidly in recent years and has been widely applied in various fields, such as machine learning, pattern recognition, natural language processing, computer vision, robotics etc. However, due to the lack of rigorous mathematical model support, the results obtained by general artificial intelligence algorithms are mostly regarded as probabilistic events and often perceived as a lack of rigor. The core requirements in industrial scenarios revolve around stability, standardization, accuracy, and repeatability, as well as close integration with mechanical equipment, processes, and production flows. Therefore, before artificial intelligence can be fully integrated into industrial systems, it is necessary to first address issues such as repeatability, reliability, and security. Industrial artificial intelligence is a system science that focuses on developing, validating, and deploying algorithms for industrial scenarios to achieve sustainable, secure, and reliable operation of systems in application environments. Industrial artificial intelligence has been widely applied in industrial manufacturing related fields such as equipment maintenance, visual inspection, quality tracking, production scheduling, material turnover, and energy efficiency optimization.