In collaboration with
Boston Consulting Group

WORLD ECONOMIC FORUM

Physical AI: Powering the New Age of Industrial Operations

WHITE PAPER

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Contents

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Foreword

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Amid mounting global pressures – from economic volatility and geopolitical disruption to growing supply-chain complexity, and labour and talent shortages – industrial operations are entering a transformative new phase. While these challenges are not new, heightened uncertainty has significantly intensified their impact, forcing a fundamental rethink of how work is organized, executed and scaled.

At this inflection point, a new era of industrial automation is emerging – powered by physical AI. These intelligent robotic systems combine perception, reasoning and action, enabling a level of autonomy and adaptability that marks a critical juncture in industrial automation. By bridging the digital and physical realms, physical AI promises to reimagine how industrial systems function – from factory floors to supply chains.

As physical AI becomes increasingly viable and strategically essential, industry leaders are seeking a deeper understanding of how to make use of these innovations for sustainable, long-term competitiveness. At such a pivotal moment, this white paper – developed through the World Economic Forum's Next Frontier of Operations initiative in collaboration with Boston Consulting Group – builds on a tradition of strategic foresight and multistakeholder engagement to chart a bold path forward.

The insights presented here draw on the collective experience of global manufacturers, robotics innovators and leading academic experts. Grounded in real-world use cases and, more importantly, the transformation journeys they represent, the paper explores how physical AI is reshaping operations, enabling new forms of human–machine collaboration and unlocking productivity at scale.

But this transformation is not solely about technology. It also requires the industrial workforce to be equipped with new skills to collaborate with intelligent systems and take on emerging roles. We invite all stakeholders – including manufacturers, policy-makers, researchers and technologists – to engage with this agenda. Together, through bold and coordinated action, we can shape a future in which intelligent automation drives inclusive, resilient and sustainable industrial growth.

Executive summary

Technological breakthroughs are pushing the boundaries of automation – tasks that were once too variable or cost-prohibitive to automate are now both technically feasible and economically viable.

Although traditional industrial robots are foundational to automation, they have long been constrained by limited adaptability and high integration costs. Today, the world is entering a new age of robotics defined by intelligence and flexibility powered by the convergence of advanced hardware, artificial intelligence (AI) and vision systems. Together, these advances are unlocking the next frontier of robotics.

Approaches such as training methods (reinforcement learning, imitation learning) and multimodal foundation models[1] for robotics, as well as dexterous hardware components (e.g. soft grippers, tactile sensors) are enabling robots to handle variability, reason in context and adapt in real time. Simplified deployment, such as through virtual training and intuitive interfaces, is significantly reducing time-to-value and expanding accessibility to small- and mid-sized manufacturers and logistics providers. Throughout this paper, the term "manufacturers" is used as a shorthand to refer to both manufacturers and logistics providers.

Such advances lead to three foundational robotics systems that will coexist in the future of industrial operations, together forming a layered automation strategy. These systems are complementary, each suited to specific combinations of task complexity, variability and volume.

- Rule-based robotics, delivering unmatched speed and precision in structured, repetitive tasks (e.g. automotive welding)

- Training-based robotics, mastering variable tasks via reinforcement learning or imitation learning (e.g. adaptive kitting)

- Context-based robotics, capable of zero-shot learning[2] and execution in unpredictable processes and new environments (e.g. robot receives, reasons and acts on instructions via natural language)

Automation is expanding opportunities across the entire industrial value chain. Early adopters are already achieving significant results. For example, Amazon, operating the world's largest robotics fleet, has demonstrated how the integration of mobile robots, AI-based sortation and generative AI-guided manipulators can improve fulfilment centre performance. By orchestrating these autonomous systems, next-generation facilities have realized 25% faster delivery, 30% more skilled roles and a 25% boost in efficiency.[3] Similarly, Foxconn applied AI-powered robotics and digital twin simulation to automate high-precision tasks such as screw tightening and cable insertion, previously considered too complex for automation. Through real-time adaptive force control and simulation-based deployment, it cut deployment time by 40% and reduced operational costs by 15%.

However, realizing such outcomes at scale demands more than cutting-edge technology. It requires a future-ready automation strategy that incorporates both technical and organizational foundations:

- Embedding the emerging AI technology stack into the existing industrial toolchain and forging ecosystem partnerships across robotics, AI and manufacturing to ensure interoperability, scalability and continuous innovation

- Workforce transformation through reskilling and upskilling to enable human–machine collaboration, and prepare workers for emerging roles such as robot supervisors, AI trainers and system optimizers

Manufacturers who act now and embed robotics as a strategic asset will lead the next phase of industrial competitiveness – shaping a future in which intelligent automation becomes a cornerstone of sustainable growth, workforce empowerment and systemic resilience.

Introduction

Manufacturers must embrace intelligent robotics now.

No longer confined to isolated efficiency gains, robotics is emerging as a strategic enabler of resilience and competitiveness.

Manufacturers today find themselves at a crossroads. Persistent labour shortages, escalating cost pressures and fragile global supply chains – amplified by geopolitical and market uncertainty – are converging to threaten productivity, profitability and resilience. At the same time, growing consumer expectations for speed, customization and sustainability demand a step-change in operational flexibility.

These intensifying pressures are accelerating the search for transformative innovations through frontier technologies. At the forefront is one undergoing profound transformation: **robotics**. No longer confined to isolated efficiency gains, robotics is emerging as a strategic enabler of resilience and competitiveness. Robotics is entering a new era – in which intelligence allows for autonomy, and physical AI redefines what machines, and by extension humans, are capable of.

Then: ***Robotics for the few. Inflexible. Static***

Since their initial deployment in the 1960s, industrial robots have reshaped manufacturing. They played a pivotal role in sectors such as automotive and electronics, where high-volume, standardized production justified the investment. However, adoption remained limited to large enterprises with highly standardized production processes. Small and mid-sized manufacturers, as well as those with variable operations, were left behind due to prohibitive cost, complexity and inflexibility.

Now and next: ***Intelligent robotics for the Intelligent Age***

But this is changing. Robotics is evolving into intelligent systems – capable of learning, adapting and acting autonomously. This shift marks a pivotal moment in the history of automation, driven by the convergence of robotics hardware, AI and vision systems.

Today, robotics is scaling – and fast. By 2023, more than 4 million industrial robots had been installed globally.[4] At the same time, advances in robotics software and hardware are enabling broader capabilities – ranging from dexterous manipulation to autonomous navigation – and significantly reducing the engineering effort required for deployment. Innovations are accelerating in response. Start-up activities and investments are surging, driven by the promise of physical AI. From foundation models for robotics (e.g. SKILD AI, Covariant, DeepMind, TRI) to general-purpose robots (such as the humanoid robots from Figure, Neura, Boston Dynamics and Apptronik), delivery in the innovation pipeline is accelerating.

As the pace of change accelerates, leaders face a set of critical questions: What technological breakthroughs are driving this shift? How is robotics already reshaping manufacturing operations, workforce roles and industrial competitiveness? And how should the technological and people foundations be laid to prepare for what's next?

This white paper provides a timely, in-depth look at how the robotics landscape in industrial operations is rapidly evolving. It goes beyond surface-level trends to provide real-world use cases, and presents a forward-looking vision of how physical AI can enable flexible, resilient and scalable automation. With achievable insights for manufacturers, technology leaders and policy-makers alike, the paper aims to serve as a strategic guide to lead – not follow – in the Intelligent Age.[5]

1 What's new: Breakthroughs in intelligent robotics

Technological breakthroughs expand the scope of automation to encompass what has been technologically unfeasible or economically unviable, and simplify implementation to deliver scalable, end-to-end automation.

The robotics landscape is undergoing a profound transformation driven by recent advances. This section outlines the primary dimensions of this transformation, which collectively mark a turning point for industrial automation.

1.1 Technological breakthroughs redefining robotic capabilities

Recent innovations in software and hardware have ushered in a step-change in robotic capability, enabling robots to perform complex tasks in dynamic environments with simpler deployment. Advances in AI and complex simulations, enabled by accelerated computing using graphics processing units (GPUs), have made it feasible to run AI models and algorithms in real time, unlocking new applications. This AI-based approach focuses on enabling robots to perceive, plan and act in complex, real-world scenarios, effectively achieving a level of physical intelligence.

Enhanced perception	Advances in sensors and AI have dramatically improved robots' ability to perceive their surroundings. Affordable high-resolution cameras, light detection and ranging (LiDAR) and next-generation tactile sensors, among other sensors, give robots richer raw inputs, while advanced computer vision algorithms (powered by deep learning) enable visual perception approaching human-level capabilities. Robots can now recognize and interpret complex environments in real time – identifying objects, recognizing their 3D orientation and assessing their physical properties – essential prerequisites for developing an understanding of how to interact with objects. These advances allow robots to "see" and comprehend an object and its environment with unprecedented clarity.
Autonomous decision-making and planning	Innovations in AI and software have enabled robots to make intelligent decisions in real time. Instead of rigid pre-programming, robots now exploit reinforcement learning and simulation to learn behaviours through trial and error in virtual environments. Advanced simulators (e.g. high-fidelity physics simulators) and domain randomization techniques (e.g. randomization of parameters such as lighting or friction) are closing the simulation-to-reality gap, so that behaviours learned in simulation transfer seamlessly to real machines. Robots also increasingly benefit from powerful foundation models that integrate vision, language and action. These models, such as Google DeepMind's Gemini Robotics[6] and Nvidia's Isaac GR00T,[7] ingest multimodal inputs and generate task-appropriate outputs – allowing for intuitive human–robot interactions and superior contextual understanding. This enables robust workflow planning: given a goal (e.g. unloading a shipment), the system determines a sequenced set of actions (use the forklift to unload, cut the banderole, open the packages, etc.). This progression enables robots to evolve from executing isolated motions to performing coherent, multistep tasks, approaching human-level task intuition and planning capabilities. In essence, robots are enabled to "think" and plan tasks with a level of flexibility and context-awareness previously unattainable.
Dexterous manipulation and mobility	Advances in materials, actuators and robotic designs have greatly expanded what robots can physically do. Hardware breakthroughs – from high-precision force-controlled motors to soft robotic grippers – give machines much more dexterity in handling objects. Robots can now grasp irregular or delicate items reliably, rather than being limited to rigid, predefined motions. This is complemented by AI-driven control software that adjusts grip and force in real time. Notably, the incorporation of a sense of touch through modern tactile sensors is a primary enabler of human-level dexterity, allowing robots to finely manipulate objects through feedback of pressure and slip. Longer battery life is significantly increasing the uptime of mobile robots, supporting more autonomous deployments and leading to extended mobility. Moreover, robotics is no longer confined to traditional form factors. Innovations have introduced quadrupeds, humanoids, mobile manipulators and hybrid forms, broadening the range of industrial applications and increasing the scope of feasible automation. These physical innovations enable robots to "act" on the world with far greater skill and autonomy.

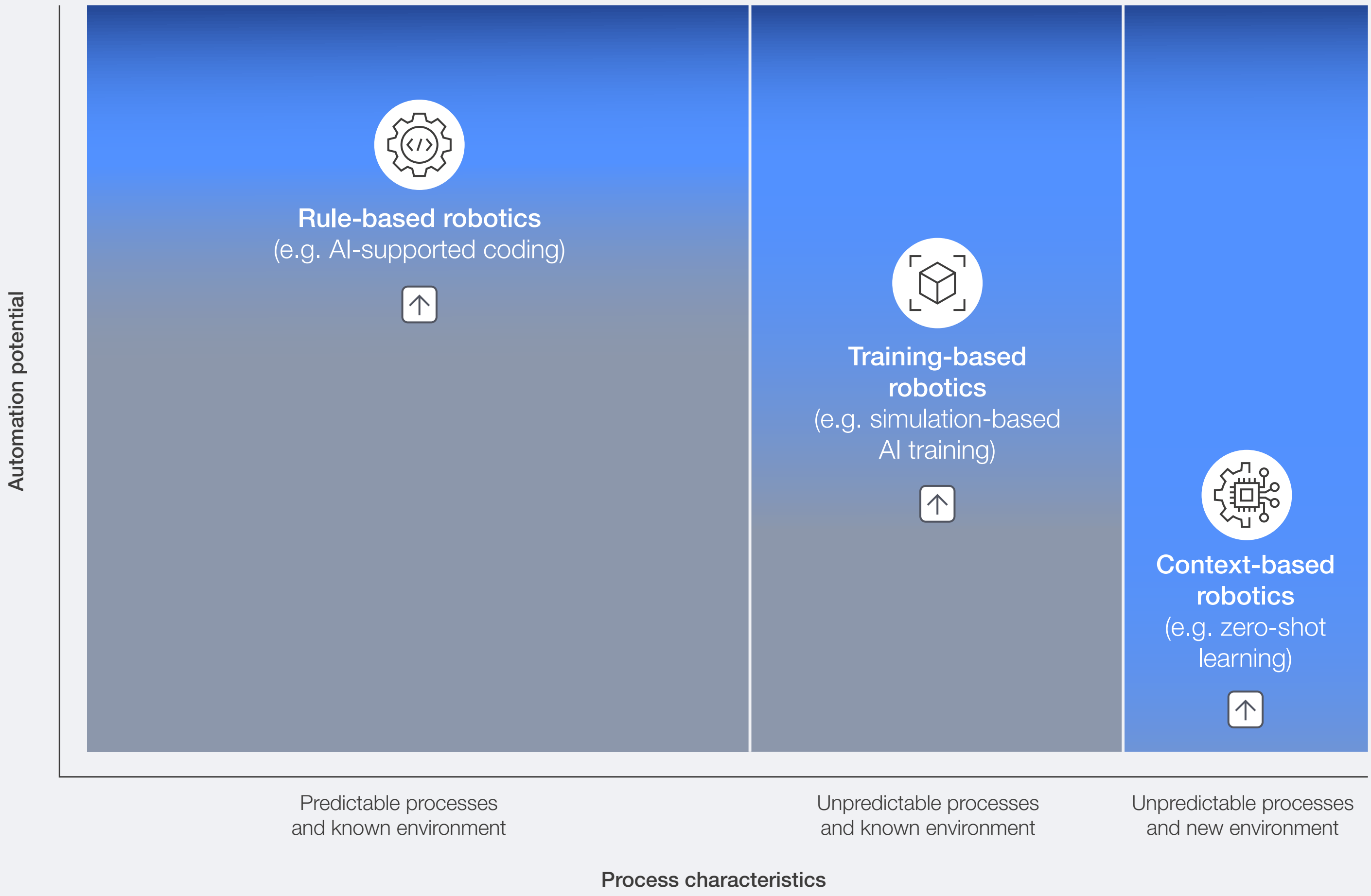
1.2 Enhanced capabilities enabling end-to-end automation

These enhanced capabilities led to the evolution of robotics from (1) **rule-based robotics** that are explicitly programmed to (2) **training-based robotics** that acquire their skill in the real world and through simulation training to (3) **context-based robotics** performing tasks autonomously without explicit training through zero-shot learning. Advances in all three robotic systems transform operations and expand the automation scope to tasks that previously could not be automatable.[8]

At the heart of this transformation, however, lies the coexistence of all three foundational robotics systems, each expanding in automation scope and sophistication. Together, they form a complementary ecosystem. Rather than replacing one another, they enable a **layered automation strategy**, aligned with operational needs (e.g. degrees of task variability) and economic considerations. Furthermore, as factories and warehouses move towards greater automation, manufacturers and warehouse operators will deploy a mix of robotic systems and embodiments – from autonomous mobile robots (AMRs) to humanoids – guided by task requirements, economic viability and process characteristics.

FIGURE 1 | **Expanding the boundaries of automation (illustrative)**

(Physical) AI considerably increases the automation scope in industrial operations



How to interpret this chart

The area of the chart maps out physical tasks (e.g. assembly steps, material handling, packaging) within a factory or warehouse. These tasks are categorized along two dimensions:

Automation potential (y-axis) is indicated through colour shading:

- **Grey:** Tasks already automatable with today's rule-based robotics
- **Blue:** Additional scope unlocked by physical AI
- **Navy:** Illustrative share expected to remain manual in the near term

Process characteristics (x-axis) are defined by parameters such as object position, orientation and size, and if the system operates in a known or new environment. Illustrative target state along different process characteristics:

→ **Predictable processes:** Parameters are either constant or vary only within a tightly controlled range – enabling deterministic, repeatable execution without the need for adaptive behaviour.

→ **Unpredictable processes:** Parameters vary significantly or cannot be anticipated.

→ **New environments:** Scenarios, layouts, objects or tasks outside the robot's training distribution (e.g. a different factory line, unfamiliar parts or altered warehouse layout).

Source: BCG, World Economic Forum, expert interviews.

The process characteristics determine which robotic system to use:

– *Rule-based robotics* continues to deliver unmatched precision and cycle-time performance in structured environments with repetitive tasks and predictable processes. These systems, ubiquitous in automotive body shops and similar settings, remain indispensable for operations where consistency and low variability are paramount. Ongoing advances in programming interfaces and AI-supported coding (such as Siemens Industrial Copilot for generative AI-assisted programmable logic controller [PLC] programming)[9] are extending their applicability and easing deployment challenges.

– *Training-based robotics* is rising to prominence in more variable environments. Enabled by advanced reinforcement-learning algorithms and simulations, these robots learn through virtual and real-world experiences. The virtualization of training significantly reduces deployment effort, as robots can be trained and validated in simulated environments before real-world rollout, thereby expanding the scope of economically viable automation. They demonstrate resilience in tasks involving controlled variation – such as flexible parts kitting or adaptive logistics – and are increasingly viable for mid-volume or non-repetitive production where rule-based robotics lacks flexibility.

– *Context-based robotics*, the newest frontier, makes use of robotics foundation models and zero-shot learning to autonomously perceive, reason and act in unfamiliar scenarios. These systems interpret high-level instructions and respond to real-world complexity without prior task-specific training, making them particularly valuable in unpredictable environments with unknown parts or new environments. Robotics foundation models form the cognitive core that enables context-based general-purpose robots – such as humanoids – to flexibly execute diverse tasks across different environments without reprogramming.

While the three system types – rule-based, training-based and context-based – form a layered automation strategy, their boundaries often overlap, and a single robot can use a hybrid approach that combines all three. For example, in a collaborative assembly cell, a robot might follow rule-based logic to perform tasks with high precision. Simultaneously, it monitors its environment using perception systems. When deviations from the expected workflow occur – such as a missing part or human intervention – the robot switches to context-based reasoning to interpret the situation and resolve it autonomously, before returning to its rule-based execution.

FIGURE 2 **Comparison of traditional and physical AI-enabled robotics**

Vision of the differences today vs. the future

	Field of automation	Implementation process	Time to industrialization	Scalability	Human-machine interaction
Today	Effective in predictable tasks or in controlled scenarios with known parts	High and complex manual effort for coding and training	Mid/long industrialization time (several months/ weeks for coding and implementation)	Limited scalability across similar set-ups or use cases	Human can adapt robot through interfaces or by guiding robot
Future	Capable of handling unpredictable scenarios and unknown parts (e.g. random bin picking, flexible material handling)	Requires relatively less engineering effort through training and self-learning (up to 70% less effort)	Accelerated deployment via few-shot/zero-shot or imitation learning (up to 50% faster time-to-value)	Scales flexibly across diverse tasks, environments and robot types	Enables intuitive control via natural language, gestures or voice commands
	Technologically feasible	**Economically viable**			

Source: BCG, World Economic Forum.

While technological advances are unlocking previously unachievable applications, the true shift is not merely in what is now technically feasible, but in what is economically viable. As highlighted in Figure 2, the future of intelligent robotics is defined by simplified deployment and more intuitive human–machine interaction, enabling reductions in implementation time and greater scalability.

As physical AI supports a wider variety of operations and becomes easier to deploy – requiring fewer specialized skills and less task-specific customization – automation becomes viable across a much broader range of operations. This evolution does not just enable new use cases, it redefines the overall economics of automation.

1.3 Limitations yet to be resolved

Vision–language–action (VLA) models are rapidly evolving as a promising path, with foundation models poised to unlock generalizable spatial reasoning capabilities.

Even as rapid advances continue, data scarcity, 3D spatial intelligence and dexterity remain challenges to be solved in the coming years:

– **Data scarcity:** Large language models (LLMs) thrived because of the ability to scrape large amounts of data from the internet. These LLMs have now read many websites and ingested many books. Physical AI also thrives on high-quality data, yet curated robotics datasets remain limited and costly, because they have to be collected in the real world. This challenge is rapidly being overcome through advances in synthetic data generation. Photorealistic rendering and domain randomization help to simulate varying lighting, textures and object shapes in virtual environments to teach robots how to grasp items in diverse real-world conditions. Combined with open-source efforts and the accelerated deployment of real-world robotic fleets, these developments are set to close the data gap and dramatically enhance learning efficiency. For example, as a first step, robotic companies such as Sanctuary AI[10] started with teleoperation – having an operator control one or more robots – while collecting data. The goal is to use this data to train the robots to operate autonomously at a later point. Developers can use technologies provided by Nvidia and other companies to produce numerous plausible futures or variations based on real or synthetic data, serving as an automatic data multiplier grounded in real physics.

– **3D spatial intelligence:** Data scarcity is chief among the reasons that perceiving, reasoning within and interacting with complex 3D environments remains a demanding task. However, progress is accelerating. Start-ups such as World Labs and Covariant, as well as academic leaders, are using simulation, real-world data and multimodal AI architectures to enable robust spatial understanding. Vision–language–action (VLA) models are rapidly evolving as a promising path, with foundation models poised to unlock generalizable spatial reasoning capabilities.

– **Generalizable dexterity with high degrees of freedom:** Achieving human-level dexterity remains a frontier challenge due to the mechanical, sensory and computational constraints. For example, robotic hands must operate with high degrees of freedom (DoF) – often more than 20 joints – which makes real-time motion planning, force control and collision avoidance very complex. Crucially, progress in 3D spatial intelligence is an enabler of dexterity: fine manipulation depends on precise perception of object geometry, pose and occlusions. Foundation models that integrate 3D scene understanding with manipulation planning will enable robots to better select stable grasps, adapt to object variability and execute corrective strategies when conditions change.

While advances in robotics continue and technological breakthroughs keep pushing boundaries, addressing emerging challenges is crucial for sustainable adoption. Key areas requiring attention include cybersecurity. Vulnerability to cyberthreats increases as factories and warehouses become increasingly software-defined and robotic systems become more interconnected. Ensuring robust cybersecurity measures is essential to protect against potential disruptions and data breaches.

2 Where it is working: Frontier applications

Intelligent robotics enables use cases across all manufacturing domains and industries, with early adopters already transforming their operations.

As intelligent robotics evolves from a niche capability into a core enabler of industrial competitiveness, adoption is accelerating across industries, functions and company sizes.

The new generation of robotic systems can now tackle complex, variable and dexterous tasks that once seemed beyond automation's reach. This section explores the breadth of emerging use cases throughout the industrial value chain and spotlights how early adopters are redefining what automation can achieve.

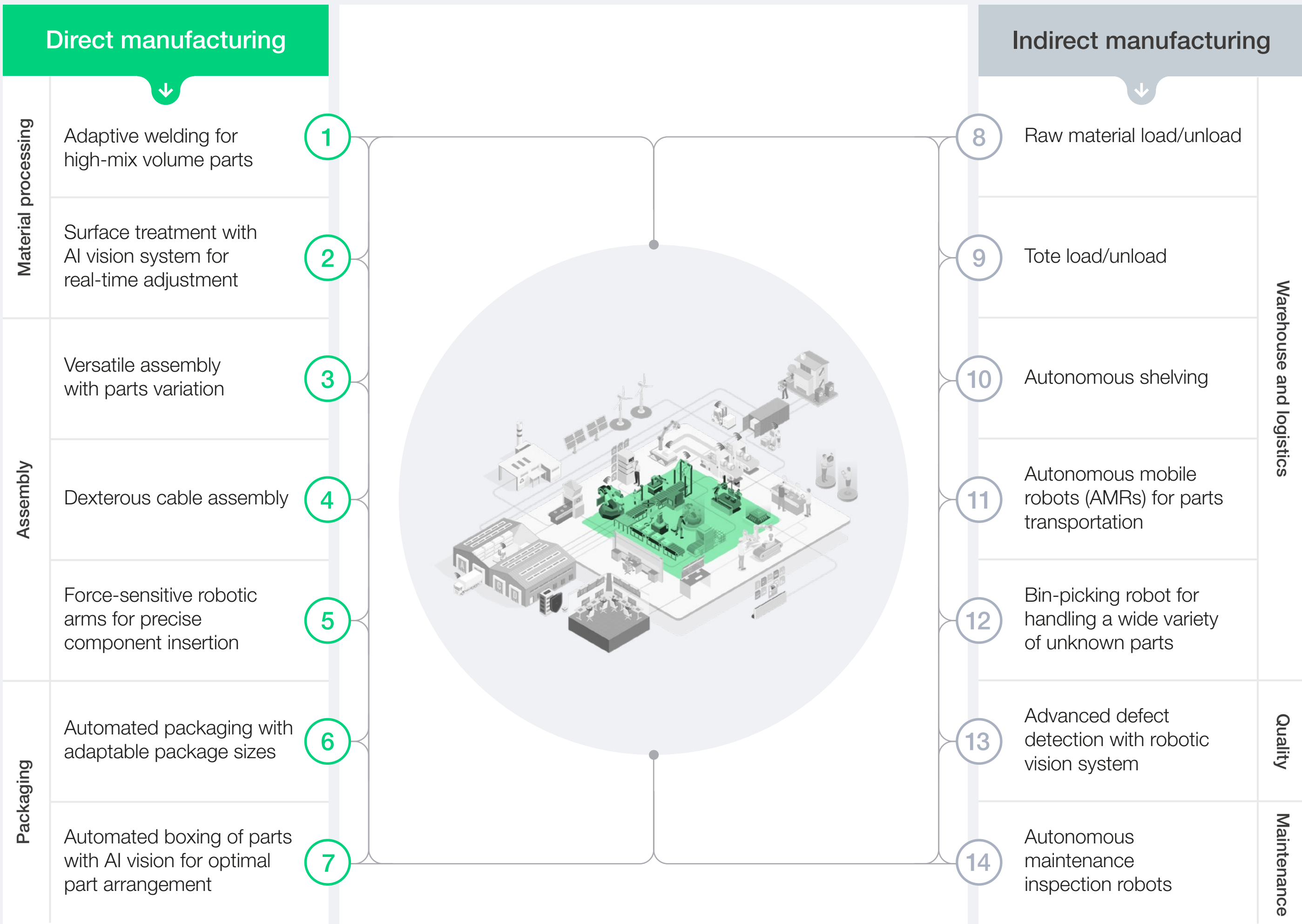
2.1 Revolutionizing the manufacturing value chain

No longer confined to isolated, high-volume tasks, today's intelligent robots are automating a broad range of operations throughout the entire manufacturing value chain – from material processing and precision assembly to packaging, intralogistics, quality inspection and maintenance. These capabilities are not theoretical; they are real and tangible and are redefining what is possible.

Across industries, physical AI is unlocking a new generation of high-impact applications (Figure 3). Innovations in direct manufacturing, such as adaptive welding, force-sensitive insertion and cable routing, are just a few examples of the new frontier. Notably, intelligent robotics is also advancing indirect manufacturing, such as warehouse logistics and inspection routines, often through mobile robots or hybrid embodiments.

FIGURE 3 **Exemplary physical AI use cases across the entire industrial value chain**

How physical AI is reshaping factory and warehouse operations



Source: BCG, World Economic Forum.

This wave of innovation underscores a broader trend: deployment is on the verge of a tipping point. Significant gains are now seen not only in industries with high-volume, low-variation environments but also in high-variation, low-volume environments. Industries that stand to benefit the most are food and beverage, metal processing, logistics and discrete manufacturing in general. Most manufacturing companies are small- and medium-sized enterprises (SMEs), which – just as much as large enterprises – stand to benefit significantly. As barriers such as high upfront investments and total cost of ownership continue to decline, the potential for SME transformation grows substantially.

2.2 Spotlight on the pioneers – transformation journeys of early adopters

As robotics reshapes the industrial operations landscape, a pioneering group of companies is charting bold new territory and redefining what is possible. By integrating intelligent robotics across previously isolated functions, they are closing the last remaining gaps in automation with physical AI. These leaders are not merely adopting tools – they are reinventing workflows, unlocking new levels of flexibility and precision, and transforming how work is done on the factory floor and in large warehouses. Their transformation journeys offer critical insights into how frontier capabilities in physical AI can be scaled effectively, demonstrating both the organizational foundation and the technical enablers required to sustain innovation at scale. The following case studies spotlight how early adopters are navigating this transformation, offering tangible proof points for what the future of industrial operations looks like in action.

CASE STUDY 1

E-commerce fulfilment

Reinventing fulfilment through the world's largest robotics operation

Amazon operates more than 1 million robots across its operations network, making it the largest user of robotics globally. These robots are deployed across 300 fulfilment centres, working alongside employees to perform repetitive tasks such as sorting, lifting and transporting packages.

The company's progress in robotics reflects an ongoing journey of experimentation and innovation, focused on continuously improving both employees' working conditions and the customer experience.

Mission

Over the past decade, Amazon has introduced a series of successive "unlocks" that applied physical AI across its fulfilment centres:

- Mobile goods-to-person robots that deliver inventory directly to employees
- Computer vision-based sortation systems to smooth inventory flow
- Mechatronic packing lines engineered to minimize use of packing materials, supporting its sustainability goals
- Robotic manipulators capable of grasping the majority of catalogue items

While these solutions improved safety and productivity, they operated in isolation. The main challenge was integrating them to enable true end-to-end transformation.

Innovation in action

In response, Amazon redesigned its fulfilment centre operating system around predictive AI planning and system interoperability. This redesign is anchored by three cornerstone technologies connecting the entire fulfilment process – from inbound receiving to outbound loading – into a single, end-to-end flow:

- **Sequoia** is an automated storage-and-retrieval system.
- **Sparrow**, an articulated manipulator, uses advanced vision and generative AI-guided motion planning to identify, pick and place roughly 60% of the items in the company's inventory, learning continuously from the industry-scale data generated every day.
- **Proteus**, a collaborative autonomous mobile robot, maps open spaces in real time, interprets social cues and charts efficient paths alongside employees, moving pallets that once required fenced zones.

← Sequoia, Sparrow and Proteus (from left to right) at work alongside Amazon employees

CASE STUDY 1

E-commerce fulfilment (continued)

Innovation in action (continued)

Amazon's application of physical AI enables robots to perceive, reason and act within the real-world environment of a fulfilment centre, while remaining anchored to the deterministic controls required for safe, at-scale operations.

Together, these systems unlock tasks that rule-based robots alone could not tackle, easing repetitive work for employees while expanding automation into previously unstructured areas of the operation.

Impact

Early deployments, including in Amazon's next-generation fulfilment centre in Shreveport, Louisiana, have yielded significant results – including improved workplace safety, creation of 30% more skilled jobs onsite, 25% faster delivery to customers and 25% efficiency improvement that will drive lower costs to customers.

A new generative AI foundation model, coordinating the movement of the entire mobile robot fleet across the fulfilment network, further improves fleet travel efficiency by 10%.

Foundation and learnings

Three foundational elements have enabled Amazon to scale intelligent robotics across its global fulfilment network:

1. Decades of computer-vision monitoring data produced an internet-scale catalogue of physical-world images and trajectories, comprising the critical training fuel for reliable physical AI models.
2. A people-first feedback mechanism, centred on front-line employees who work alongside robots, allows engineering teams to directly iterate with users to ensure that automation solutions reduce friction rather than introduce new islands of automation that do not seamlessly integrate into broader workflows.
3. Amazon designs, manufactures and deploys its robotics solutions in-house. Co-location of hardware, AI and operations teams enables rapid build–measure–learn cycles and accelerates rollout.

Together, these enablers – massive data, employee co-design and an integrated build pipeline – helped Amazon to scale physical AI safely and consistently across the world's largest fulfilment network.

With this shift, the need for higher-skilled workers (such as roles in reliability maintenance engineering) increased by 30%. Amazon has implemented the Career Choice[11] programme to provide tuition support and reimbursement for books and fees for degrees and certifications designed to upskill employees into in-demand and high-paying career paths, and through its mechatronics and robotics apprenticeship programme employees can advance their careers and increase their hourly wages by up to 40%.[12]

CASE STUDY 2

Electronics manufacturing

Adaptive robotics automating highly versatile assembly operations

In response to rising labour costs and the global trend towards localized production, Foxconn is promoting the vision of a "scalable AI-powered robotic workforce". It outlined a three-stage AI-enabled factory development process: digital twin simulation design, human-robot collaboration and, finally, **embodied intelligence robotic factories.** This phased transformation reflects Foxconn's broader ambition: not only to automate tasks, but to architect an intelligent production ecosystem to unlock higher industrial value and operational scalability across its global manufacturing network.

CASE STUDY 2

Electronics manufacturing (continued)

Mission

As part of **Foxconn's** continuous drive for operational excellence and sustainable innovation, they found that traditional rule-based robotics fell short in automating precision tasks like screw tightening and cable insertion **due to the need for high accuracy, adaptability and precise force control.** Foxconn is innovating these precision tasks through robotics powered by AI and digital twin technologies. By integrating intelligent automation, real-time simulation and precision control, it enabled faster deployment, higher reliability and scalable implementation across global manufacturing operations – laying the groundwork for the next generation of smart, AI-integrated factories.

Innovation in action

Foxconn used **Nvidia's platform** alongside **AI-powered robotic arms** integrating precise socket pose estimation and real-time motion planning. This enabled highly accurate and collision-free operations, unlocking two new opportunities:

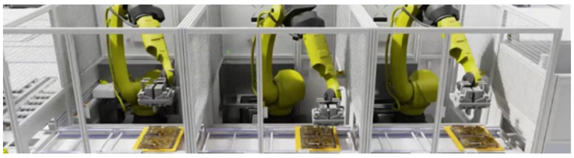
- **Screw tightening:** AI-enabled robots learned optimal motion trajectories and torque application through reinforcement learning – improving consistency and cycle time, and reducing defects.
- **Cable insertion:** Previously this could not be automated due to complexity, but it is now enabled through real-time force and trajectory adjustments – allowing dynamic grip and movement to accommodate part variation.

The virtualization of the training and the integration of physical AI enabled fast deployment across multiple sites, forming a scalable blueprint for future Foxconn smart factories.

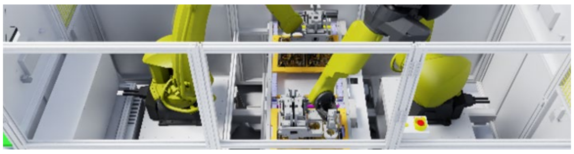
High-precision tasks powered by AI and simulation

1 Screw-tightening workcells simulation

Simulation of a flexible workcell approach using different types of robotic arms.



Three workcells for robotic arm screw-tightening



Single workcell for dual-arm cooperative screw-tightening

2 Cable insertion

Using two different approaches: manual and with robotic arms.

Manual cable insertion

Cable insertion with robotic arms

Impact

By creating digital twins of their production lines for rapid virtual simulation, testing and validation, Foxconn **cut deployment time by 40%.** AI-driven robotics **improved cycle times by 20–30%** and enhanced force feedback and motion control, **reducing error rates by 25%.** Virtual validation eliminated costly trial-and-error in physical environments, **reducing operational costs by 15%.** Moreover, the self-adjusting force and trajectory of the AI-driven robotic arms **boosted precision and reliability,** achieving a higher success rate than human workers in complex assembly tasks.

Foundation and learnings

Technology: Simulation-to-reality transfer enabled large-scale deployment by accelerating AI model adaptation and reducing physical trial and error.

People: Engineers were upskilled via hands-on training in digital twin simulation, AI-based robot programming and toolchains from Nvidia's graphics collaboration platform Omniverse. This gave them skills in virtual commissioning, adaptive control and data-driven optimization, transitioning them from engineers to AI-integrated automation architects.

Partnerships: Foxconn collaborated with service providers, such as Nvidia, to provide simulation and AI-powered robotics infrastructure. It also partnered with the manufacturing ecosystem (e.g. Fanuc and Techman) to co-develop scalable automation strategies, which were instrumental during this transformation.

3 How it scales: Technology platforms and partnerships

A new physical AI technology stack for robotics is emerging, and strategic partnerships will be essential to enable integration, scalability and ecosystem-wide success.

Before intelligent robotics can scale, the right foundation must be in place. Technology alone is not enough – what matters is how systems are built, integrated and evolved through collaboration.

3.1 The new physical AI technology stack

As robotics technology matures, a new physical AI stack is emerging that fundamentally differs from the traditional robotic platform. This emerging technology stack is structured around five layers as highlighted in Figure 4.

FIGURE 4 **Emerging physical AI technology stack**

Application
Interfaces and tools for end-user interaction and system integration, including APIs, connectors and intuitive HMIs for monitoring and control

Simulation/training
Virtual environment, tools and data platforms for robot development and testing, using synthetic data generation, high-fidelity simulators and digital twins to enable accurate "sim-to-real" transfer

Operating system
Backbone of the stack for hardware abstraction, process coordination and component communication; manages task scheduling and integrates frameworks such as a robot operating system (ROS) to ensure standardization and interoperability

Edge hardware
On-device processors for real-time AI inference and sensor fusion, enabling autonomous decisions with minimal latency and without cloud reliance

Robotic hardware
Mechanical base, including actuators, controllers and sensors/vision systems, that enables the robot to act, sense and perceive

Source: World Economic Forum, BCG.

> Scalable impact requires the seamless integration of the AI technology stack into the existing manufacturing environment.

New entrants – ranging from AI-first start-ups (e.g. Sereact, Covariant) to tech giants (e.g. Nvidia, Tesla, Apple, Google) – are joining traditional players in reshaping the ecosystem. A vital innovation lies in the simulation/training layer. High-fidelity world models, kinematic, physics-based photorealistic simulations (depending on the application) and synthetic data generation enable the development and deployment of robust AI skills. Some software-only start-ups have built upon existing hardware to upgrade their capabilities (e.g. Covariant, Intrinsic). At the same time, vertically integrated companies have emerged to provide a solution across the entire technology stack (e.g. Neura, Figure, Tesla, Boston Dynamics). In most cases, their innovations belong in the space of context-aware robotics using the humanoid form factor.

Independent of whether the approach entails a modular vs. vertically integrated solution within the layered technology stack, scalable impact requires the seamless integration of the AI technology stack into the existing manufacturing environment. Today, manufacturers rely on a complex industrial software tool chain from which product and process data from diverse sources needs to be ingested and integrated with adjacent automation equipment to ensure system-level intelligence.

Along with traditional integrators, new service providers have entered the market, including those offering robots-as-a-service (RaaS) models for deployment, operation and maintenance. This has broadened accessibility and lowered the barrier for companies that lack internal capabilities.

3.2 Strategic partnerships are essential

In this fast-evolving landscape, strategic partnerships offer one effective pathway for manufacturers who want to harness the latest robotics innovations. No single company can realistically develop all of the advanced capabilities alone at the pace at which technology is progressing. The obstacles are especially high for smaller enterprises that lack the resources to build up the required capabilities independently. The most successful manufacturers identify the right partners with whom to collaborate.

By forging strong partnerships with technology providers, research institutions and peers within and across the industry, manufacturers can stay at the forefront of change and employ collective expertise. For example, a car manufacturer might collaborate with an AI start-up to co-develop a robotic-equipped assembly line, while also working with a university robotics lab on new manipulation techniques.

Such collaboration helps companies keep up with rapid advances – tapping into partners' specialized knowledge in AI, sensors or software updates – rather than falling behind the state of the art. It also reduces integration hurdles: when robot makers, AI developers and factory engineers plan solutions together, they can anticipate and solve compatibility issues early, ensuring smoother deployment. Similarly, partnerships invite co-creation of solutions tailored to real operational needs. Manufacturers can guide integrators and equipment suppliers on what is needed on the factory floor, and in turn receive highly customized, robotic systems that no party could have built in isolation.

Beyond technical innovation, collaboration can also unlock new markets and capabilities, risk and investment sharing, and early alignment with regulators and standards bodies.

In summary, the rise of the physical AI technology stack is not just about new technology stacks, but also about building new relationships and ecosystems. It is a world in which vertically integrated robot companies work alongside component specialists, and end users collaborate closely with innovators. Embracing this ethos of building partnerships and ecosystems is how manufacturers will navigate the new age of intelligent robotics – staying agile, sharing investments, benefits and risks, and co-creating the next generation of industrial automation.

4 Who leads it: Empowering the new industrial workforce

Robotics must be embedded not only as a short-term cost lever but also as a long-term strategic enabler of excellence – led by people empowered by the skills needed to succeed.

The rise of physical AI is not just a technological advance; it is a structural transformation in how industrial work is designed, executed and experienced.

Leaders are advised to move beyond viewing single robotics use cases as only a short-term cost reduction tool and instead embrace those new automation opportunities as a strategic enabler of long-term operational success and resilience.

4.1 A target picture for robotics and workforce development

This shift requires a clear automation target picture considering all robotics applications and an execution plan – one that also looks at long-term workforce development. Intelligent robotics, when deployed strategically, can adapt to variability, reduce operational errors and sustain performance amid workforce shortages or supply-chain disruptions.

One of the most immediate and tangible impacts is on workplace safety: robotics can absorb tasks involving lifting, repetitive motion or exposure to hazardous environments – common causes of injury. At Amazon, sites integrating robotics have seen a 15% reduction in incident rates, as employees transition into roles focused on oversight, diagnostics and continuous improvement.[13] Additionally, human-centric system designs enable workers to transition into safer, more fulfilling roles that employ their cognitive strengths. For example, robust.AI develops robots as intuitive, supportive teammates to reduce complexity and improve collaboration on the shop floor.[14]

4.2 A shift in skills and roles

This technological leap also redefines the role of humans in industrial settings. As physical AI automates manual tasks, certain traditional job categories may be displaced. According to the World Economic Forum's [Future of Jobs Report 2025], "robots and autonomous systems" are projected to be the leading driver of net job displacement by 2030.[15] Yet this displacement is not just a disappearance – it is a transition. New skilled roles are emerging that centre on supervising intelligent systems, resolving edge cases and optimizing system performance.

FIGURE 5 | Emerging roles and tasks across the value chain driven by physical AI

Physical AI automation frees up humans for higher-level tasks

	Direct manufacturing	Indirect manufacturing			
	Material processing, assembly and packaging	**Manufacturing engineering**	**Logistics**	**Quality control**	**Maintenance**
Today	Operators manually process and assemble parts. Tasks require precision, manual machine operation and full attention. Changeovers and packaging are fully manual and labour-intensive.	Manufacturing engineers design, implement and optimize production systems, largely experience-driven. Updating inflexible automation requires high manual effort.	Workers manually move materials using forklifts or carts. Human coordination is needed, leading to inefficiencies, accidents and misplacements.	Products are visually inspected by workers. This is slow, subjective and prone to human fatigue. Random sampling may miss defects.	Reactive or preventive maintenance schedules are followed (independent of machine conditions). Engineers rely on visual checks and logs, making issues hard to foresee.
Future	**Scenario**				
	AI-enabled robots perform welding, assembly and packaging using real-time system feedback. Systems adapt to product and task variations automatically.	Production systems are software-driven, intelligent and adaptive. Engineers plan factories, integrate intelligent robots and visual-based quality control systems.	AI-driven autonomous mobile robots handle materials end-to-end, ensuring the right parts are delivered on time.	Vision-guided robotic arms scan every unit in real time and perform automated inspection tests.	AI-powered systems are becoming self-sufficient, with robots and drones handling some maintenance and inspection tasks while continuously generating data.
	Tasks				
	– Supervise robotic workflows – Train robots for new tasks – Resolve exception cases	– Optimize adaptive system – Oversee digital process design – Cross-disciplinary integration	– Monitor robotic fleets – Reconfigure robot routes – Manage system alerts	– Strategic oversight – Audit flagged defects – Optimize quality control	– Perform complex repairs – Interpret data – Improve system
	Skills				
	– Systems thinking – Digital literacy – Robot programming/ teaching	– Advanced digital and AI skills – Systems thinking – Creativity	– Systems thinking – Digital literacy – Workflow design and safety	– Analytical thinking – AI and big data – Creativity	– Technical skills – Analytical thinking – AI and big data

Source: BCG, World Economic Forum.

This shift is well illustrated in the evolving landscape of tasks and skills as shown in Figure 5. For instance:

– Machine operators are evolving into robot technicians, automation supervisors and AI system trainers

– Logistics workers are becoming fleet coordinators for mobile robots

– Quality-control specialists are assuming roles as AI-aided inspectors, interpreting algorithmic outputs rather than manually reviewing each item

– Maintenance teams are transitioning from reactive fixes to predictive diagnostics enabled by sensor data and AI forecasting

– Manufacturing engineers shift from designing and maintaining systems to optimizing adaptive, AI-driven robotic solutions

As roles centred on robots gain importance, companies that have dedicated robotic teams will be at the forefront of this revolution. Leaders will move from managing output through labour and process improvements to embedding AI robotics into the business model with a focus on ethics, cybersecurity and continuous innovation. These changes signal a broader transformation in workforce roles. The future workforce will place greater emphasis on:

– **Judgement and management by exception:** making nuanced decisions when robots fail

– **Data interpretation and decision-making:** reading system analytics to guide operations and improvements

– **Continuous improvement and system optimization:** identifying opportunities to enhance the performance of AI-enabled workflows

These examples illustrate how roles and tasks are evolving, and this topic will become increasingly important as intelligent robotics – among other frontier technologies – continues to reshape industrial work.

4.3 The new workforce imperatives

Success in the robotics era hinges on seamless interdisciplinary collaboration across engineering, IT, operations and other functions, coupled with a culture of lifelong learning that keeps skills current for every role. To unlock this potential, leaders must strengthen change-management capabilities that steer transitions and embed continuous innovation, learning and adaptability.

In the age of intelligent robotics, no transformation is complete without people transformation. Strategic workforce planning is essential to ensure that intelligent robotics delivers not only operational value but also long-term economic and social resilience. A clear automation target picture and a vision of future roles, tasks and required skill sets must guide structured and continuous reskilling and upskilling initiatives to enable the industrial workforce of tomorrow.

In response to the people transformation and skills evolution underway, the World Economic Forum has launched a Human–Machine Collaboration initiative. This initiative focuses on redefining human–machine synergy and delivering a model framework to enable workforce transition through skill mapping and talent strategies. The overarching goal is to ensure that people remain central to frontier technology-driven transformation.

Conclusion: Time for action

The robotics revolution is no longer on the horizon – it is already under way, transforming industrial operations.

For leading manufacturers, intelligent robotics has moved beyond experimentation to become a cornerstone of operational excellence, adaptability and long-term resilience.

The impossible is now viable. What once seemed out of reach – due to technological complexity or economic constraints – is now feasible, thanks to rapid advances in physical AI, simulation environments and robotic systems design. The target state includes a layered automation strategy in which rule-based, training-based and context-based robotics coexist, enabling system-level intelligence and providing a foundation for future growth. As integration becomes faster and more scalable, robotics is shifting from a niche capability to a competitive imperative.

Technology must be integrated, not isolated. Realizing the full potential of intelligent robotics demands a robust technological infrastructure that unifies and supports individual robotic solutions. A new AI technology stack is emerging that must be seamlessly integrated into the industrial software toolchain already in place to enable end-to-end system-level intelligence. Achieving this degree of integration is not a solo effort. Success will hinge on building strong, collaborative ecosystems that will distinguish those who can scale intelligent robotics from those who stall in isolated deployments.

People must lead the transformation. Strategic foresight is essential to align robotics adoption with operational variability, production models and long-term workforce development. Manufacturers must move beyond viewing single automation use cases only as tools for short-term cost reduction and instead embrace them as catalysts for long-term sustained value creation. As job roles evolve, upskilling and reskilling efforts will be critical to ensure that workers are prepared to oversee, optimize and extend intelligent systems. Only through a people-first approach can companies embed robotics into their DNA in a way that is both sustainable and inclusive.

Manufacturers must lead, not follow. The moment for leadership is now. Manufacturers who delay risk missing the momentum of rapidly converging technology and economic tipping points. Those who act boldly will not only unlock productivity and resilience but also shape the future of industrial operations – a future that is intelligent, adaptive and deeply collaborative. The time to build it is today.

The Forum is committed to collaboration. Going forward, the World Economic Forum will continue to serve as a vital platform for shaping the future of intelligent robotics. By convening leading innovators, policy-makers and industry pioneers, the Forum will encourage cross-sector collaboration, share cutting-edge insights and help scale its responsible adoption. The goals are to illuminate the path forward and enable stakeholders to navigate this new era with confidence, agility and purpose.

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