



NATIONAL SECURITY  
COMMISSION ON  
**ROBOTICS FOR ADVANCED  
MANUFACTURING**

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# Preliminary Report

CO-CHAIRS

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SPECIAL COMPETITIVE  
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# Letter from the SCSP President & Commission Co-Chair

The United States is entering a decisive period for its industrial future. Advances in artificial intelligence, robotics, and autonomy are bringing intelligent machines into the physical economy. This emerging era of “physical AI” could raise productivity, strengthen supply chains, expand defense production, improve workplace safety, create new opportunities for workers, and revitalize American manufacturing.

Physical AI at scale will define the next industrial era, and the United States is not on a trajectory to lead it. America remains at the frontier of many technologies that form the “brain” of modern robotics—including artificial intelligence, computer vision, autonomy, and software—but it has not translated those strengths into comparable capacity to deploy robots, produce robotic systems at scale, or manufacture critical components domestically. China, by contrast, has established a substantial and growing advantage across much of the robotics value chain. Unless the United States changes course, that gap will widen and increasingly constrain America’s industrial and national security choices. Reversing this trajectory is why SCSP initiated this Commission.

We do not have the luxury of waiting. A software advantage that cannot be embodied, manufactured, deployed, and sustained at scale will not be sufficient to secure American industrial leadership. Meeting this challenge does not mean abandoning the innovation model that gives the United States its edge, nor does it mean copying China’s top-down, state-directed approach. It means mobilizing America’s own strengths—private-sector dynamism, world-leading research, deep capital markets, regional manufacturing ecosystems, and skilled workers—to accelerate responsible adoption and production. That effort must also strengthen cybersecurity, advance effective standards, and expand opportunity for American workers.

This Preliminary Report presents to the Co-Chairs of the National Security Commission on Robotics for Advanced Manufacturing the initial assessment of that challenge and the opportunity within it. Its central finding is a consequential imbalance: the United States remains a leader in robotics innovation, but it lacks sufficient scale in deployment, production, and critical components.

At the center of this imbalance is an adoption-and-scale challenge. Greater deployment generates operational data, learning, and manufacturing volume. Those gains improve performance and lower costs, encouraging further adoption, yet many

manufacturers—particularly small and medium-sized firms—face capital constraints, limited technical expertise, uncertain returns on investment, and a lack of trusted guidance. These barriers suppress the very scale that would make robotic systems more capable, adaptable, and affordable. Waiting for perfect technology or perfect evidence is not a neutral position. It is itself a strategic choice.

The preliminary findings provide reasons for confidence as well as signs of concern. Robotics can help manufacturers address persistent labor shortages, compete more effectively, improve quality, reduce workplace injuries, and take on work they might otherwise be unable to perform. At the same time, adoption remains constrained by hardware dependencies, commercialization and financing gaps, incomplete standards, cyber-physical risks, fragmented public institutions, and shortages of technicians, engineers, and researchers. Left unaddressed, these weaknesses will reinforce one another.

Public debate too often casts robotics as a binary choice between people and machines. The reality is more complex. American manufacturers could face as many as 1.9 million unfilled positions by 2033 if persistent workforce challenges are not addressed. Robotics can help fill dangerous, physically demanding, and chronically vacant roles while augmenting the skill and judgment of existing workers. It can also make it more viable to keep production in the United States. At the same time, wider robotics deployment will reshape tasks and skill demand, and some workers may face disruption. American workers must therefore be active participants in this transition, not passive bystanders. That will require aligning education and training with shop-floor needs, expanding credible pathways into technical careers, and helping incumbent workers acquire the skills to work alongside increasingly capable systems.

That is why we convened this Commission and why we are releasing these findings before our final report. This Preliminary Report offers a diagnosis organized around four mutually reinforcing pillars: the national framework, talent pipeline, adoption at scale, and innovation ecosystem. Our final report will build on this foundation and propose recommendations for federal, state, and regional leaders; manufacturers and technology companies; educators and workforce-development organizations; workers and labor representatives; and the other institutions whose participation will be necessary.

No single sector can build a self-reinforcing cycle of robotics adoption, production, and innovation on its own. The decisions made in the next few years about technology

adoption, industrial capacity, workforce development, and national strategy will determine whether America's leadership in artificial intelligence translates into durable industrial strength.

I am grateful for the bipartisan support this effort has received and for the engagement of the commissioners, manufacturers, workers, researchers, educators, investors, and other experts whose experience and input have shaped our work. I look forward to working with Senators Budd and Slotkin as we begin to formulate policy recommendations to address the issues identified in this report.

The United States possesses extraordinary advantages: world-leading software and research institutions, innovative manufacturers and entrepreneurs, deep capital markets, and a workforce capable of meeting great technological challenges. But those advantages will not organize themselves. With strategic focus, practical cooperation, and sustained action, America can lead not only in the intelligence that powers the machines of the future, but in the industrial capacity, resilient supply chains, and skilled workforce needed to build, deploy, and sustain them.

A handwritten signature in black ink, reading "Ylli Bajraktari". The signature is fluid and cursive, with a prominent initial "Y" and "B".

**Ylli Bajraktari**  
Co-Chair

## About the Commission

The National Security Commission on Robotics for Advanced Manufacturing was created to address one of the most consequential missions of our time: ensuring that the United States not only leads the world in the technologies that power modern robotics, but also possesses the industrial capacity, supply chains, and skilled workforce needed to build, deploy, and sustain those systems at scale. By examining the convergence of artificial intelligence, robotics, and autonomy—“physical AI”—the Commission seeks to help translate American innovation into greater productivity, stronger supply chains, expanded defense production, safer workplaces, and new opportunities for American workers.

The Commission is an initiative of the Special Competitive Studies Project (SCSP), a nonpartisan, not-for-profit project focused on strengthening America’s long-term competitiveness as artificial intelligence and other emerging technologies reshape our national security, economy, and society. The Commission is co-chaired by Senator Ted Budd (R-NC), Senator Elissa Slotkin (D-MI), and SCSP President and CEO Ylli Bajraktari. This bipartisan effort reflects a shared conviction that sustaining American technological leadership requires more than invention. It requires the ability to manufacture advanced systems, deploy them throughout the production base, secure their underlying supply chains, and prepare American workers to use and improve them.

To pursue that mission, the Commission brings together leaders from manufacturing, technology, academia, research, investment, and national security. Its work is organized around four mutually reinforcing pillars: the national framework, talent pipeline, adoption at scale, and innovation ecosystem. The Commission’s Preliminary Report provides an initial diagnosis of America’s position and the barriers preventing robotics innovation from reaching industrial scale. Its Final Report, scheduled for March 2027, will build on that assessment with recommendations for government, industry, educators, workforce-development organizations, workers, and other institutions whose participation will be necessary to secure American leadership in the era of physical AI.

## Co-Chairs:

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**Senator Elissa Slotkin** (D-MI)

**Ylli Bajraktari**, President & CEO, *Special Competitive Studies Project*

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\*Dr. Howard stepped down as commissioner in June 2026 to focus on her new role as President of Spelman College. We thank her for her invaluable service.

## About the Preliminary Report

This Preliminary Report presents the National Security Commission on Robotics for Advanced Manufacturing's initial diagnosis of the United States' position at the convergence of artificial intelligence, robotics, and advanced manufacturing. Its purpose is to establish an evidence base for the Commission's final recommendations by identifying the structural conditions that prevent American strengths in artificial intelligence, software, research, and entrepreneurship from translating into comparable leadership in robotics deployment, production, and critical components.

The analysis is organized around four interdependent pillars: the national framework, the talent pipeline, adoption at scale, and the innovation ecosystem. It examines robotic systems used in advanced manufacturing, including fixed industrial robots, collaborative systems, autonomous mobile robots, and emerging general-purpose platforms where they are relevant to production. The report does not assume that every robotic system or component must be manufactured domestically. Rather, it considers where concentrated or adversary-linked dependencies create strategic vulnerability and where domestic or allied capacity is necessary for economic resilience and national security.

The findings draw on publicly available data, academic and industry research, Commission deliberations, briefings and site visits, and engagements with manufacturers, workers, technology developers, systems integrators, researchers, educators, investors, and other experts. Because robotics technologies, markets, and deployment models are evolving rapidly—and because the available evidence remains uneven in several areas—these findings are preliminary. They are intended to clarify the problems that must be addressed and the questions that must be resolved before the Commission issues its Final Report in March 2027. That report will build on this diagnosis with recommendations for federal, state, and regional leaders; manufacturers and technology companies; educators and workforce-development organizations; workers and labor representatives; and other institutions whose participation will be necessary to secure American leadership in physical AI.

# Table of Contents

|                                                                                                                                                                                                |           |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>Executive Summary</b>                                                                                                                                                                       | <b>8</b>  |
| <b>Strategic Premise: Physical AI Leadership Will Be Won Through Deployment and Production at Scale</b>                                                                                        | <b>12</b> |
| Finding 1: Physical AI at scale will define the next industrial era, and the United States is not on a trajectory to lead it.                                                                  | 12        |
| <b>National Framework: Interlocking Risks and Gaps Require National Coordination</b>                                                                                                           | <b>18</b> |
| Finding 2: A supply-demand paradox is preventing the U.S. robotics flywheel from starting.                                                                                                     | 18        |
| Finding 3: Fragmented institutions, unmanaged strategic risk, and weak public confidence compound to block coordinated action.                                                                 | 21        |
| <b>Talent Pipeline: Labor Scarcity Creates an Opening for Robotics, but Skills Gaps Constrain Adoption</b>                                                                                     | <b>28</b> |
| Finding 4: The effects of robotics on employment are ambiguous and not predetermined.                                                                                                          | 34        |
| Finding 5: Labor shortages and skills misalignment limit manufacturing at scale and robotics deployment.                                                                                       | 38        |
| <b>Adoption at Scale: New Capabilities Are Expanding the Market, but Persistent Barriers Hold Manufacturers Back</b>                                                                           | <b>49</b> |
| Finding 6: The industrial robotics landscape is undergoing a transformation in deployment dynamics driven by AI-assisted programming, low-code interfaces, and open-space mobile manipulation. | 51        |
| Finding 7: Robotics adoption across manufacturing remains constrained by lack of knowledge, internal capability gaps, and unsteady demand signals.                                             | 54        |
| <b>Innovation Ecosystem: Supply-Chain, Financing, Data, and Cost Constraints Prevent U.S. Robotics Firms from Scaling</b>                                                                      | <b>58</b> |
| Finding 8: Systematic cost disadvantages and a financing gap keep U.S. robotics firms from scaling production.                                                                                 | 59        |
| Finding 9: Supply chain bottlenecks for physical components and data keep U.S. robotics too expensive and too static.                                                                          | 65        |
| <b>Looking Forward: Converting U.S. Robotics Innovation into Industrial Scale</b>                                                                                                              | <b>72</b> |
| Finding 10: A national mission is needed to start the U.S. robotics flywheel.                                                                                                                  | 72        |
| <b>Appendix &amp; Supplemental Content</b>                                                                                                                                                     | <b>75</b> |
| Commission Advisors and Staff                                                                                                                                                                  | 75        |
| Glossary of Terms                                                                                                                                                                              | 76        |
| Form Factor Finance Research                                                                                                                                                                   | 80        |
| Wage Trend Research                                                                                                                                                                            | 87        |

## Executive Summary

The United States leads in many of the technologies that power intelligent machines, but it has not translated those strengths into comparable capacity to build, deploy, and sustain robotics across its manufacturing base. Physical AI offers an opportunity to raise productivity, improve workplace safety, address persistent labor shortages, and expand domestic production. Realizing those benefits will require turning America's innovation advantage into industrial scale.

The Commission's initial assessment identifies a reinforcing set of barriers. Manufacturers need affordable, reliable systems and the skills to integrate them; robotics firms need predictable demand, suitable capital, components, and operational data to improve performance and lower costs. When deployment remains limited, each constraint reinforces the others. China's much larger installed base and dense supplier networks give its firms an advantage in this cycle, while the United States retains substantial strengths in research, software, entrepreneurship, and allied partnerships.

The ten preliminary findings below organize this challenge around four interdependent pillars: the national framework, talent pipeline, adoption at scale, and innovation ecosystem. They point toward a national mission that advances economically sustainable deployment, strengthens domestic and trusted allied production, and prepares workers to benefit from technological change. The Commission's Final Report, scheduled for March 2027, will develop recommendations to translate this diagnosis into measurable action.

### Finding 1

**Physical AI at scale will define the next industrial era, and the United States is not on a trajectory to lead it.**

The United States lags in industrial robot deployment and production scale compared to global competitors—China in particular—which disrupts the self-reinforcing cycle of the robotics flywheel. Ultimately, deployment at scale rather than just AI model capability will determine leadership in the emerging era of physical AI.

### Finding 2

**A supply-demand paradox is preventing the U.S. robotics flywheel from starting.**

Manufacturers hesitate to adopt robotics until systems become cheaper and more easily integrated. Yet robotics firms cannot lower costs and improve performance without deployment at scale. This dynamic creates a coordination failure that the market is unlikely to overcome on its own.

**Finding 3**

**Fragmented institutions, unmanaged strategic risk, and weak public confidence compound to block coordinated action.**

Federal robotics initiatives are minimal and scattered across multiple agencies without a unified strategy or single authority to drive national-scale outcomes. This lack of coordination is compounded by public anxieties over job displacement and cybersecurity and supply-chain vulnerabilities tied to foreign dependencies to prevent cohesive action.

**Finding 4**

**The effects of robotics on employment are ambiguous and not predetermined.**

The impact of automation on employment is not fixed, as it simultaneously involves job displacement, job transformation, and new job creation. Whether net employment expands or contracts ultimately depends on the pace of adoption and whether job creation and task redesign keep up with initial task displacement.

**Finding 5**

**Labor shortages and skills misalignment limit manufacturing at scale and robotics deployment.**

A persistent mismatch in skills constrains robotics deployment because manufacturers seeking to use robotics lack the qualified talent required to scale production and integrate automated systems. Traditional apprenticeships struggle to keep pace with rapid technological changes, prompting a near-term shift toward agile micro-credentials. Additionally, weak STEM pipelines threaten long-term American innovation.

|           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Finding 6 | <p><b>The industrial robotics landscape is undergoing a transformation in deployment dynamics driven by AI-assisted programming, low-code interfaces, and open-space mobile manipulation.</b></p> <p>Advances like AI-assisted programming and collaborative robots are expanding the feasibility of automation beyond rigid, high-volume production environments. However, safety frameworks and performance standards are struggling to keep pace with these highly flexible and dynamic new capabilities.</p> |
| Finding 7 | <p><b>Robotics adoption across manufacturing remains constrained by lack of knowledge, internal capability gaps, and unsteady demand signals.</b></p> <p>Many manufacturers lack the specialized knowledge and digital infrastructure required to successfully deploy robotic systems. Furthermore, unsteady demand signals and overly narrow return-on-investment metrics make it difficult for firms to justify the upfront capital required for automation.</p>                                               |
| Finding 8 | <p><b>Systematic cost disadvantages and a financing gap keep U.S. robotics firms from scaling production.</b></p> <p>U.S. robotics startups face a commercialization "valley of death" because traditional venture capital timelines do not align with the lengthy, capital-intensive requirements of hardware manufacturing. Additionally, heavy reliance on opaque, concentrated global supply chains limits domestic production scale and creates significant strategic bottlenecks.</p>                      |
| Finding 9 | <p><b>Supply chain bottlenecks for physical components and data keep U.S. robotics too expensive and too static.</b></p> <p>Concentrated component supply raises costs and strategic risk. Limited deployment and incompatible data systems constrain learning; simulation and synthetic data can help, but require validation in real operating conditions.</p>                                                                                                                                                 |

#### Finding 10

#### **A national mission is needed to start the U.S. robotics flywheel.**

Overcoming these systemic barriers requires a unified national mission focused on scaling the development and deployment of robotic systems across the industrial base. This effort must coordinate private-sector dynamism with strategic public goals to enhance domestic production capacity, lower costs, and secure American technological leadership.

# Strategic Premise: Physical AI Leadership Will Be Won Through Deployment and Production at Scale

The next era of technological leadership will belong to the nations that can turn artificial intelligence (AI) into industrial power: embedding intelligence in machines that sense and act in the physical world—physical AI—then manufacturing those systems at scale and deploying them throughout the production base. The United States is not yet positioned to lead that transition. Whether it does will depend on choices made now.

The stakes extend well beyond the robotics industry itself. Manufacturers and other end users will deploy physical AI across production, warehousing, logistics, and related operations. Its largest economic effects may therefore appear in the productivity, output, and competitiveness of the industries using these systems, rather than in the revenues of robotics companies alone. National leadership in physical AI is, in this sense, a question of economy-wide competitiveness.

America leads in invention but has repeatedly failed to convert it into scalable, sustained production—from semiconductors, where U.S. firms pioneered the foundational technology but ceded much of the manufacturing base, to solar photovoltaics, where American breakthroughs ultimately gave way to Chinese dominance in production. Nowhere is that challenge more consequential than at the nexus of artificial intelligence and robotics for advanced manufacturing.

## **Finding 1: Physical AI at scale will define the next industrial era, and the United States is not on a trajectory to lead it.**

Leadership in physical AI will depend on productive deployment and resilient production capacity, not model capability alone. Like other general-purpose technologies, AI produces broad productivity gains when firms make complementary investments and reorganize production around it; in manufacturing, that means embedding intelligence in machines and putting those systems to productive use by augmenting human workers.<sup>1</sup>

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<sup>1</sup> Erik Brynjolfsson, et al., [The Productivity J-Curve: How Intangibles Complement General Purpose Technologies](#), American Economic Association (2021); Georg Graetz & Guy Michaels, [Robots at Work](#), Review of Economics and Statistics (2018).

Physical AI shares the diffusion dynamics of earlier general-purpose technologies such as electricity and the internet: the economic gains arrive not when the technology is invented but when it is installed, integrated, and worked into ordinary production—a process that can take decades. Physical AI adds a deployment challenge: realizing its value often requires a capital-intensive, site-specific combination of software, sensors, actuators, compute, connectivity, manufactured hardware, integration expertise, and trained workers. Broad adoption of robotics and automation could help U.S. manufacturers improve productivity and compete at scale, but adoption depends on making these systems practical for firms beyond a handful of large users.<sup>2</sup>

Deployment can create a reinforcing cycle—the robotics flywheel. Adoption generates operating data, integration experience, and production volume. Those inputs can improve reliability, shorten integration time, and reduce costs; better performance and economics can then support further adoption. Scale can also reveal shortcomings in manufacturing processes and products that are difficult to see in a laboratory or a limited pilot. As firms redesign processes and systems in response, deployment becomes an input to the next generation of robotics innovation—not merely a way to capture the benefits of existing technology. Deployment also strengthens domestic industrial capacity when the resulting demand and operating lessons reach the firms that design, build, supply, and integrate subsequent generations of systems.

The extent of deployment matters because it determines how many firms can participate in that cycle. Concentrated adoption can produce substantial learning within individual companies while leaving much of the manufacturing base without the operating experience needed to improve and expand its use of robotics.

As Figure 1 illustrates, the U.S. cycle is interrupted by frictions in financing, integration, data and standards, component and sub-component production, and workforce adoption and readiness. The FANUC and Amazon Robotics examples in the figure illustrate how repeated use can produce learning effects that a laboratory prototype cannot. However, relying on a few large adopters has clear limits—a major logistics operator, for instance, may use its field experience to build proprietary systems without those insights benefiting smaller manufacturers. Supplier relationships, integrators, shared standards, and workforce capabilities help determine whether learning at

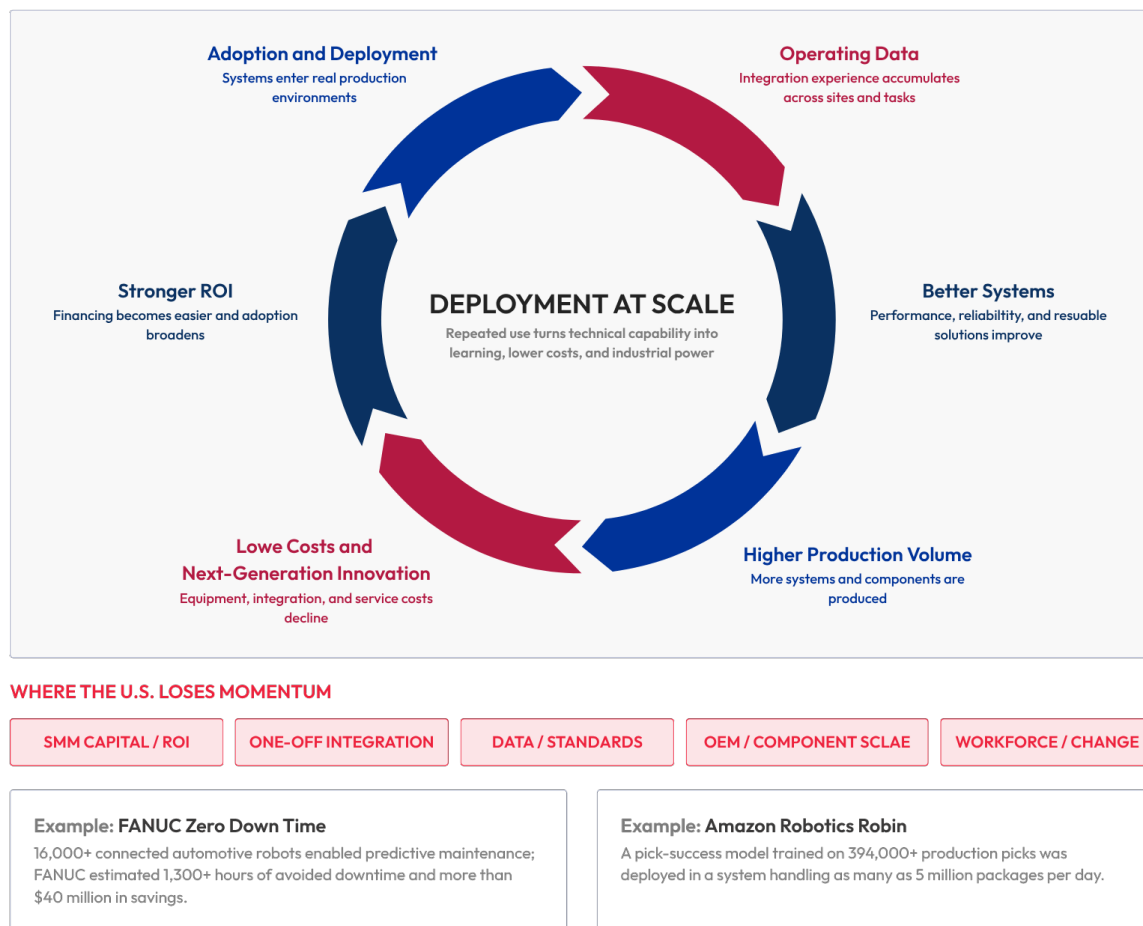
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<sup>2</sup> Georg Graetz & Guy Michaels, [Robots at Work](#), The Review of Economics and Statistics (2018); [Measurement Science for Robotics and Autonomous Systems](#), National Institute of Standards and Technology (last accessed 2026).

individual firms spreads across the wider production base. Two firms are not on their own evidence of an economy-wide learning curve.<sup>3</sup>

## Figure 1 | The Robotics Deployment Flywheel Is Not Yet Compounding Across U.S. Manufacturing

*Takeaway: Deployment creates data, integration experience, and volume that improve performance and economics—and can generate the next generation of innovations. U.S. frictions limit how widely those gains spread.*



Source: SCSP Analysis, FANUC America, Amazon Science<sup>4</sup>

<sup>3</sup> [U.S. Lags China in Factory Robot Deployment by 5 to 1 Ratio](#), International Federation of Robotics (2025); [China Tops World Record of 2 Million Factory Robots](#), International Federation of Robotics (2025).

<sup>4</sup> [FANUC America's Robot LINKi Zero Down Time \(ZDT\) Available on all FANUC Robots](#), FANUC America (2018); Shuai Li, et al., [Demonstrating Large-Scale Package Manipulation Via Learned Metrics of Pick Success](#), Amazon Science (2023).

The United States' competitive position reflects a flywheel that turns but does not compound broadly. It has strong capabilities in frontier AI, conventional robotic hardware, AI-enabled robotics, research infrastructure, venture formation, and systems integration. Yet venture capital is often poorly matched to hardware timelines, and integration capacity is uneven. Its weaker links are domestic industrial-robot production scale, depth in key components, and broad manufacturing adoption—especially among smaller manufacturers.<sup>5</sup> Because deployment at scale generates learning, attracts suppliers and investment, and supports further cost reductions, the longer these weaknesses persist, the harder it will become for the United States to close China's lead in robotics adoption and production capacity.<sup>6</sup>

This report does not assume that every robot or component must be produced domestically. The strategic question is where dependence creates vulnerability and where domestic or allied capacity is essential—a question the Innovation Ecosystem section of this report takes up directly.

China's position is different, but not simply the mirror image of America's. China's deployment scale gives its firms more opportunities to improve manufacturing processes, test systems under varied operating conditions, and feed those lessons into new products. That does not guarantee a lead in frontier innovation. It does mean that a persistent U.S. deployment gap could become an innovation gap, including in robotics for advanced manufacturing. The United States retains advantages on some frontier-model and high-impact innovation measures, but leading Chinese AI models have become increasingly competitive.<sup>7</sup>

The comparative data show both U.S. strengths and the scale of the gap. On the International Federation of Robotics' measure of industrial robots, the United States ranked eighth worldwide in robot density in 2024, with roughly 307 robots per 10,000 manufacturing employees—a fraction of the Republic of Korea's 1,220, but higher than China's density.<sup>8</sup> In absolute terms, China has a decisive lead. In 2025, Chinese factories installed approximately 354,200 industrial robots—59% of worldwide installations—compared with approximately 38,400 in the United States. Chinese suppliers accounted for 55% of installations in their domestic market, although China remains dependent on

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<sup>5</sup> [The Robot Deficit](#), Special Competitive Studies Project (2026).

<sup>6</sup> Robert D. Atkinson, [How Innovative Is China in the Robotics Industry?](#), Information Technology and Innovation Foundation at 1, 6–8 (2024).

<sup>7</sup> [The 2026 AI Index Report](#), Stanford University Human-Centered Artificial Intelligence (2026).

<sup>8</sup> [Robot Density Surges in Europe, Asia, and Americas](#), International Federation of Robotics (2026).

foreign suppliers for some advanced components.<sup>9</sup> Most industrial robots installed in the United States were imported.<sup>10</sup> By the end of 2024, Chinese firms had over two million industrial robots operating in factories, more than five times the U.S. stock of 393,700. These figures measure industrial robots; they do not capture the full range of newer systems, including mobile robots and humanoids. Comparable deployment data for those systems are needed before drawing broader conclusions about leadership in physical AI. The strategic issue is therefore not a simple ranking. It is whether the United States can convert innovation into broad deployment and durable production capacity.

Figure 2 summarizes this asymmetry.

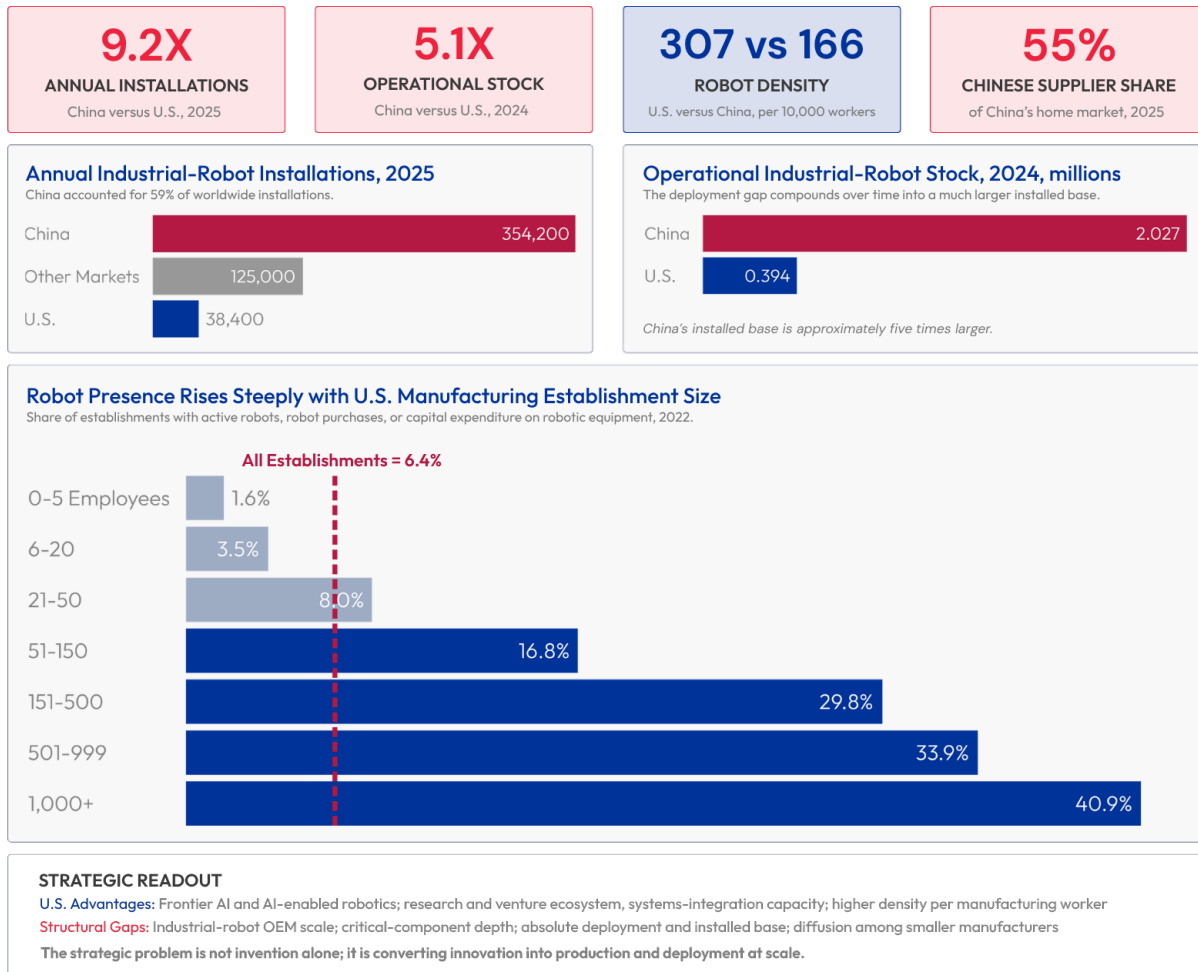
### Figure 2 | The United States Leads in Key Innovation Inputs but Trails in Deployment Scale and Diffusion

*Takeaway: China leads in annual industrial-robot installations and installed stock; U.S. industrial-robot density was higher in 2024, but adoption remains uneven across manufacturers.*

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<sup>9</sup> [China Installs 59 Percent of World's Industrial Robots](#), International Federation of Robotics (2026).

<sup>10</sup> [U.S. Lags China in Factory Robot Deployment by 5 to 1 Ratio](#), International Federation of Robotics (2025); [China Tops World Record of 2 Million Factory Robots](#), International Federation of Robotics (2025).



Source: International Federation of Robotics<sup>11</sup>

The American robotics flywheel will not reach self-sustaining speed through isolated technical advances alone. It requires coordinated action to address barriers to demand and deployment, integration, finance, components, standards, workforce readiness, and data sharing. The next section, National Framework, explains why this is a strategic problem requiring national coordination.

<sup>11</sup> [World Robotics Report 2026](#), International Federation of Robotics (2026); [World Robotics Report 2025](#), International Federation of Robotics (2025).

## National Framework: Interlocking Risks and Gaps Require National Coordination

The U.S. robotics challenge is a system problem before it is a technology problem. The United States retains major strengths in artificial intelligence, computer vision, autonomy, software, research, and entrepreneurship. Still, these strengths have not combined to produce deployment, industrial capacity, operating data, supply-chain visibility, or public confidence at the scale required for durable leadership in physical AI.<sup>12</sup>

The weaknesses reinforce one another. Limited deployment suppresses orders for hardware, components, integration, and services. Limited production and field experience keep cost and uncertainty high, deepening reliance on foreign suppliers for robotics hardware components and systems. That dependence creates economic and security risks by tying U.S. production to supply chains controlled and influenced by America's chief adversary, China. Fragmented institutions and the absence of an overarching strategy reduce policy coherence and scale, while public support for expanded use of robotics in manufacturing remains limited in the face of uncertain effects on employment.

To develop a framework for national action, the Commission evaluated where national leadership is needed, and where existing efforts have fallen short.

### **Finding 2: A supply-demand paradox is preventing the U.S. robotics flywheel from starting.**

Manufacturers are waiting for robotic systems to become cheaper, more adaptable, easier to integrate, and better proven. At the same time, many improvements in performance and cost depend on the deployment volume that manufacturers provide. The market is trapped in a first-mover problem: each firm has reason to wait for someone else to absorb the uncertainty, while the ecosystem needs enough early deployment to generate production scale, operating evidence, service capacity, and confidence. Flywheels do not start themselves.

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<sup>12</sup> [The Robot Deficit](#), Special Competitive Studies Project at 4-15, 20-28 (2026); [National Action Plan for U.S. Leadership in Advanced Manufacturing](#) Special Competitive Studies Project at 4-13 (2026).

This is not solely a financing problem, a technology problem, or an awareness problem. It is a coordination failure connecting adoption, production, data, cost, integration capacity, and talent. At the firm level, delay can be prudent. Repeated across the industrial base, the same decision prevents the market from generating the learning and scale that would make adoption less risky for everyone.

## **Ecosystem Stagnation Compounds Adoption Risk**

A manufacturer must weigh uncertain demand and utilization against the full cost and disruption of integration. Hesitance to adopt is an unsurprising outcome. A later adopter can observe which applications worked, how long integration took, whether the vendor provided adequate support, what workforce skills are needed, how to address safety considerations, and whether the expected return materialized. They can also benefit from established support networks and skilled workers.

Adopting without local precedent is different. A firm in this position discovers failure modes, develops new workflows, helps the integrator refine the solution, and generates knowledge that benefits vendors and future customers. It must also identify and develop the workforce skills needed to sustain its robotics deployment. As a result, the costs and risks of moving first are often greater than those for later adopters following an established path.

This is especially true for small and medium-sized manufacturers (SMMs). Their adoption decision is generally limited by scarce capital, low tolerance for downtime, and a lack of robotics engineers and technicians on their staff. The Department of Commerce's National Institute of Standards and Technology (NIST) found that these firms often lack sufficient robotics expertise, knowledge of system capabilities and limitations, and access to unbiased guidance when evaluating automation.<sup>13</sup>

Research using the Census Bureau's Annual Survey of Manufactures reinforces this. Regional adoption is positively associated with the presence of integrators and peer manufacturers using robotics.<sup>14</sup> This is because firms face fewer barriers, lower risk, and more available talent when they are in proximity to other adopters, but without firms willing to take on the risks of moving first, such an ecosystem can't form.

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<sup>13</sup> John A. Horst, et al., Best Practices for the Integration of Collaborative Robots into Workcells Within Small and Medium-Sized Manufacturing Operations, National Institute of Standards and Technology at 1-10 (2021).

<sup>14</sup> Erik Brynjolfsson, et al., The Characteristics and Geographic Distribution of Robot Hubs in U.S. Manufacturing Establishments, United States Census Bureau at 15-23 (2023).

## **Low Deployment Prevents Supplier Innovation and Economies of Scale**

When firms wait to deploy, robot vendors see irregular projects rather than predictable orders. Component suppliers cannot invest confidently in production capacity without stable demand signals. Integrators struggle to turn one-off engineering projects into repeatable solutions. Field-service networks remain thin, and training providers receive weak signals about the roles and competencies employers will need at scale. Prospective workers do not see pathways to stable careers. Prices stay high, talent remains scarce, and risk remains elevated.

Deployment of robots on manufacturing lines also creates knowledge that cannot be developed elsewhere. Robots in working factories encounter product variation, imperfect fixturing, legacy equipment, sensor degradation, maintenance constraints, worker interaction, and edge cases that controlled demonstrations may not reveal. Those experiences provide feedback and data to users, integrators, component suppliers, software developers, and robot manufacturers. This data can in turn be used to produce better products and execute more efficient deployments.

Deployment is also necessary to test and demonstrate new technologies. For startups and innovators, this is a key part of both developing and proving new technologies. Without the ability to deploy at scale, new technologies struggle to progress past early stages. In this way, production and use are a critical part of the innovation process itself.<sup>15</sup>

## **The Supply-Demand Paradox is a Market Failure and Requires Intervention to Solve**

The challenges industry faces to start the robotics flywheel without unified engagement through industrial strategy are the result of a series of market failures. The decision by one firm to adopt robotics benefits the entire local and national robotics ecosystem, but firms do not take those external benefits into account when making their adoption decisions.

Correcting this market failure requires external incentives or coordination to enable companies to shift their cost-benefit analysis to capture the external benefits of

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<sup>15</sup> [National Action Plan for U.S. Leadership in Advanced Manufacturing](#), Special Competitive Studies Project at 4, 13 (2024).

adoption to the country. National leadership can provide that coordination and establish the conditions to start the robotics flywheel.

### Figure 3 | Supply-Demand Paradox Causal Loop

*Takeaway: Fragmented demand suppresses hardware, integration, and service scale; limited scale keeps cost and uncertainty high; high cost and uncertainty further suppress demand.*



Source: SCSP Analysis

### **Finding 3: Fragmented institutions, unmanaged strategic risk, and weak public confidence compound to block coordinated action.**

While the United States remains a global leader in foundational robotics research, its ability to scale, deploy, and secure these technologies is constrained by systemic friction. The central challenge facing American leadership is not a lack of innovation or federal activity, but a threefold structural bottleneck: organizational fragmentation

across agencies, a contested public narrative surrounding automation, and critical supply chain and cybersecurity vulnerabilities.

Overcoming these obstacles requires viewing robotics as a coherent national strategic enterprise rather than a collection of independent programs. Unlocking national-scale impact demands aligning dispersed federal initiatives into clear pathways for manufacturers, building public trust through transparent and worker-centric deployment, and safeguarding domestic physical and digital infrastructure against foreign dependencies.

## **Fragmented Federal Programs Do Not Provide a Coherent Path from Research to Deployment**

The United States does not lack federal robotics activity. Agencies and programs support foundational and applied research, standards development, manufacturing adoption, technology demonstration, cybersecurity, workforce development, procurement, and industrial-base capacity. The core issue is that these programs are not coordinated. They are spread across at least four executive departments and numerous agencies. Their missions often overlap, and programs compete rather than collaborate. No single institution or individual is accountable for whether the country ultimately develops, manufactures, deploys, and securely operates robotics at national scale.<sup>16</sup>

For manufacturers, fragmentation appears as a series of disconnected transactions. Technical assistance may come from one program, financing from another, cybersecurity guidance from a third, and workforce support from state or local institutions. Each operates under different timelines, eligibility rules, terminology, and measures of success. Firms may encounter many entry points but no authoritative pathway from problem identification through integration and repeat adoption.

Robotics firms face the inverse problem. A startup may secure research funding without access to manufacturing capacity, procurement demand, customer financing, or field-service capacity. A strategically important component supplier may fall outside programs organized around complete systems. Integrators may hold the most valuable deployment knowledge but lack a mechanism to share lessons across testbeds and

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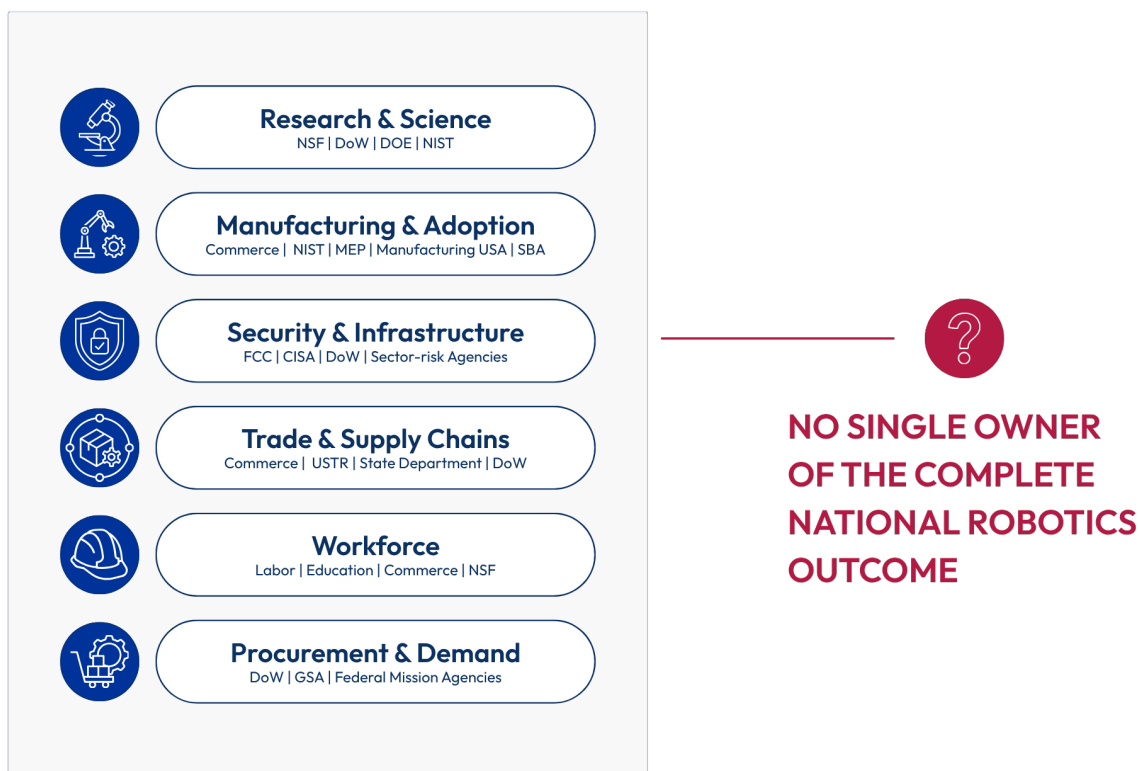
<sup>16</sup> [Winning the Race: America's AI Action Plan](#), The White House at 5–10, 18–22 (2025); Henrik I. Christensen, [A Roadmap for U.S. Robotics: Robotics for a Better Tomorrow, 2024 Edition](#), Computing Community Consortium at 3–4, 10–11 (2024).

regions. The system funds individual activities, but it does not reliably carry firms and technologies from assessment to durable market capacity.

This report is not the first time this diagnosis has been made. The National Robotics Initiative coordinated more than \$250 million across more than 300 projects before the National Science Foundation (NSF) ended the program in 2022. The American Society of Mechanical Engineers (ASME) proposed a National Robotics Council in 2019, and Professor Henrik Christensen’s 2024 U.S. robotics roadmap called for cross-agency coordination linking research with development, demonstration, adoption, competitiveness, and security. That the diagnosis of the underlying challenges is consistent over time strongly suggests a structural gap rather than a temporary program failure.<sup>17</sup>

#### Figure 4 | Federal Robotics Ecosystem Map

*Takeaway: Federal agencies possess relevant authorities, but no node is accountable for whether the complete robotics flywheel produces national-scale outcomes.*



<sup>17</sup> Margaret Martonosi & Susan Margulies [NRI Sunset Announcement](#), National Science Foundation (2022); [Accelerating U.S. Robotics for American Prosperity and Security](#), American Society of Mechanical Engineers at 3-6 (2019); Henrik I. Christensen, [A Roadmap for U.S. Robotics: Robotics for a Better Tomorrow, 2024 Edition](#), Computing Community Consortium at 3-4, 10-11 (2024).

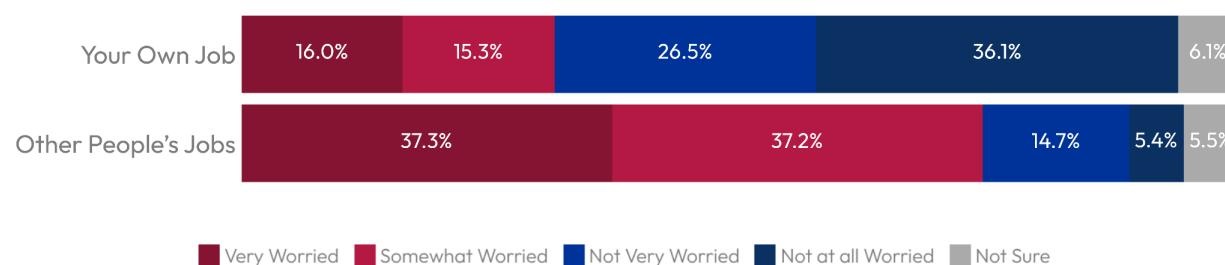
## Public Support Depends on Visible Benefits and Credible Protections for Workers

Robotics adoption is not only a technical and financial decision. It is also a decision about trust. Workers must believe systems can operate safely and that deployment will include credible training, transparency, and accountability. Managers must believe that they have the flexibility for temporary setbacks and that vendors will provide reliable support. Communities and policymakers must believe automation will strengthen firms and regional opportunity rather than merely subsidize worker displacement and job losses. Public legitimacy is therefore an essential condition for deployment, not a communications task that begins after a system is installed.

Recent robotics-specific polling shows substantial concern about displacement, but also a gap between perceived societal and personal exposure. In a July 2026 Breakwater Strategy/YouGov survey of 1,306 U.S. adults, 74% were worried that robots would take other people's jobs within five years. Among 582 employed respondents, 31% worried that a robot would take their own job. Acceptance also varied sharply by application: 63% were comfortable with robots working in grocery stockrooms and loading docks, and 59% with robots cleaning floors and aisles, compared with 39% at self-checkout. The pattern suggests that attitudes are shaped by proximity, direct interaction, and whether a robot is perceived as replacing a visible human role.<sup>18</sup>

### Figure 5 | Americans' Concerns About Robots Taking Jobs in the Next Five Years

*Takeaway: Americans perceive robotics as a broad employment risk, but comfort varies sharply by task and proximity.*



Source: Breakwater Strategy<sup>19</sup>

<sup>18</sup> [Robotics Omnibus Survey—July 2026](#), Breakwater Strategy (2026); [New Survey: How Americans Are Thinking About Robots, and Why It Matters for the Companies Deploying Them](#), Breakwater Strategy (2026).

<sup>19</sup> [Robotics Omnibus Survey—July 2026](#), Breakwater Strategy (2026).

Public opinion is not defined only by fear. A March 2025 Pittsburgh Robotics Network survey of 642 adults found that 44% expected robotics to contribute to more manufacturing in the United States and 62% preferred or were more likely to use robotics created domestically. Respondents were most encouraged by applications in hazardous environments, disaster response, and space exploration, while expressing greater concern about self-driving vehicles, military uses, and law enforcement. These results suggest that confidence strengthens when the benefits of robotics are concrete and readily understood: safer work, domestic production, and capabilities that keep people out of danger.<sup>20</sup>

A credible public case must address concerns about job loss and worker displacement. Trust will not be built by denying those risks. It will be built through transparent safety and workforce plans, worker participation, credible training and redeployment, clear accountability, and evidence that productivity gains translate into safer work, stronger firms, good wages, and visible career opportunities. Government, employers, educators, and labor unions can help make this case through credible policy, training, and worker-engagement initiatives that build support for responsible automation.

## **Foreign Component and Software Dependencies Create Supply-Chain and Cyber Risk**

Robotics increasingly sits at the intersection of industrial competitiveness, critical infrastructure, data policy, worker safety, and national security. A modern robot often combines cameras and other sensors, wireless connectivity, proprietary software, cloud services, remote maintenance, and the ability to act physically inside a facility. The same features that create value also create dependence and attack surface.

Risk is not uniform. A network-isolated packaging cell does not have the same risk profile as a connected mobile robot operating inside a defense production facility. An allied supplier with a substantial U.S. presence is not equivalent to an adversary-controlled vendor. National coordination is required precisely because industry competitiveness and security cannot be separated, but neither can they be collapsed into a single category.

China's robotics strategy, as set out in its second Five-Year Development Plan for the Robotics Industry, links domestic deployment, component capacity, standards activity,

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<sup>20</sup> [Americans See Promise in Robotics, But Few Expect Their Own Jobs to Change](#), Pittsburgh Robotics Network (2025).

and overseas market expansion.<sup>21</sup> In 2024, Chinese-owned robotics manufacturers captured 57% of their home industrial-robot market, while China as a whole accounted for more than half of global installations of industrial robotics. That scale supports supplier investment, customer feedback, integration experience, lower unit costs, and greater influence over interfaces and standards.<sup>22</sup>

The U.S. position is more complicated than a simple domestic-versus-foreign divide. Japanese and European firms supply much of the industrial robot hardware used in American factories and often maintain substantial U.S. production, employment, integration, and service operations. These allied suppliers strengthen U.S. capacity, though, as the Innovation Ecosystem section notes, allied assembly can still rest on Chinese sub-tier components. At the same time, the United States has few major U.S.-headquartered industrial robot manufacturers and remains dependent on overseas production for critical subsystems, spare parts, firmware, and specialized support.<sup>23</sup>

Permanent magnets illustrate how a lower-tier input can become a strategic chokepoint. In 2024, China accounted for approximately 60% of global mine production of the rare-earth elements used principally in high-performance magnets, 91% of refined output, and 94% of sintered permanent-magnet production. These magnets are necessary components in most motors and actuators used for, among other things, industrial robots.<sup>24</sup> In 2025, China weaponized this leverage and implemented export restrictions, triggering disruptions across the industrial supply chains of the United States and its allies and partners.<sup>25</sup>

Beyond component supply chain security, risks also arise from foreign-sourced parts, especially those sourced from Chinese suppliers. The recent national security determination that added foreign-produced advanced robotic devices to the Federal Communications Commission (FCC) Covered List—discussed further in the Adoption at Scale and Innovation Ecosystem sections—outlined this. Advanced robots are equipped

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<sup>21</sup> Xiaogang Song, [Understanding the New Five-Year Development Plan for the Robotics Industry in China](#), International Federation of Robotics (2022).

<sup>22</sup> [The Robot Deficit](#), Special Competitive Studies Project at 16–22, 25–31, 38–42 (2026); [China Tops World Record of 2 Million Factory Robots](#), International Federation of Robotics (2025).

<sup>23</sup> [The Robot Deficit](#), Special Competitive Studies Project at 9–15, 25–28 (2026).

<sup>24</sup> [Rare Earth Elements](#), International Energy Agency (2026).

<sup>25</sup> Gracelin Baskaran & Meredith Schwartz, [Rare Earth Export Restrictions One Year Later](#), CSIS (2026).

with high-fidelity sensors, collect significant amounts of data on their surroundings, are highly networked, and vulnerable to data exfiltration or remote disruption.<sup>26</sup>

These risks are not theoretical. In early 2026, a software engineer discovered a security vulnerability in robot vacuums produced by a Chinese company that granted him access to live camera feeds, microphone audio, and floor plans from nearly 7,000 devices across 24 countries. Even absent the vulnerability, much of the data he accessed was being transmitted to cloud servers in China as part of the vacuum's standard operations.<sup>27</sup> Before that, in 2025, security researchers discovered a pre-installed backdoor in a popular quadruped robot manufactured by Unitree Robotics, a large Chinese robotics company. The backdoor enabled the surveillance of customers around the world and the unauthorized ability to control the robots' action from anywhere.<sup>28</sup>

## **A National Framework is Needed to Coordinate Efforts, Ensure Public Trust, and Protect American Security**

The issues of interagency coordination, public trust, and national security cannot be solved without a clear national framework. Such a framework is necessary to maximize efficiency, measure success, and provide cohesive messaging. Three of its binding constraints—the workforce that must operate these systems, the firms that must decide to buy them, and the ecosystem that must develop, build, and supply them—are the subject of the sections that follow.

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<sup>26</sup> National Security Determination on the Threat Posed by Foreign-Produced Advanced Robotic Devices, FCC (2026).

<sup>27</sup> Sean Hollister, [The DJI Romo Robovac Had Security So Poor, this Man Remotely Accessed Thousands of Them](#), The Verge (2026).

<sup>28</sup> Sam Sabin, [Chinese Robotics Manufacturer Left Backdoor In Product](#), Axios (2025).

# Talent Pipeline: Labor Scarcity Creates an Opening for Robotics, but Skills Gaps Constrain Adoption

U.S. manufacturers face a persistent labor shortage. According to a 2024 study by Deloitte and the Manufacturing Institute, the industry will need to fill approximately 3.8 million jobs by 2033, and up to 1.9 million of those roles could go unfilled. The persistence of reported shortages suggests that they extend beyond pandemic-era disruption, according to multiple studies conducted by Deloitte and The Manufacturing Institute from 2018 through 2024. Across those studies, 65% of manufacturing executives cited talent acquisition and retention as their primary business challenge.<sup>29</sup> This gap is driven by a combination of fast-evolving skill requirements and a demographic crunch.

First, this section analyzes the root causes of the labor shortage: demographic shifts and a declining worker value proposition. Next, it evaluates automation's impact on total employment. Finally, it addresses the skill misalignments and pipeline bottlenecks—across training, credentialing, and STEM—that affect whether domestic workers can secure robotics-adjacent roles.

## An Aging Workforce and Weak Entry Pipeline are Deepening Manufacturing Shortages

The manufacturing talent pipeline is constrained as the current workforce ages out of the labor pool faster than new entrants arrive. According to the Bureau of Labor Statistics, the median age in the manufacturing sector is now 44 years old, exceeding the U.S. national workforce median of 42.1 and standing well above younger sectors such as technology (40.7) and retail (37.7). Furthermore, the U.S. Census Bureau data show that 40% of manufacturing jobs are at firms where at least one in four workers is 55 or older, compared to just 10–14% in consumer service sectors.<sup>30</sup> While service industries draw from a steady pool of younger labor, manufacturing faces a concentrated demographic crunch that hits specialized physical trades—such as industrial welding—particularly hard, as retiring master technicians cannot be replaced as quickly as entry-level service staff.

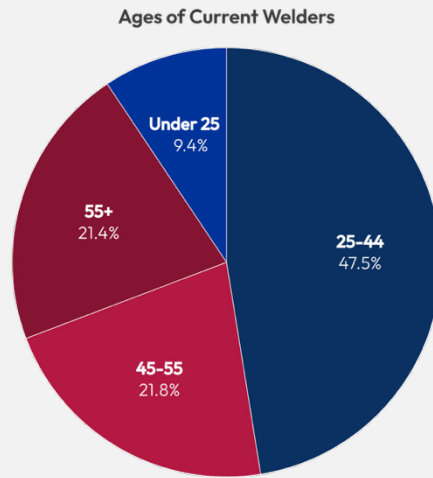
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<sup>29</sup> John Coykendall, et al., [Taking charge: Manufacturers support growth with active workforce strategies](#), The Manufacturing Institute (2024).

<sup>30</sup> [Labor Force Statistics from the Current Population Survey](#), U.S. Bureau of Labor Statistics (2026); Martha Stinson & Sean Wang, [Firms in Production Sectors and Northern States Have Some of the Highest Shares of Older Workers](#), U.S. Census Bureau (2025).

## Figure 6 | The Welding Case Study

- Over 157,000 welders (43% of current workforce) will retire within the next 15 to 20 years.
- Young workers, those under the age of 25, make up less than 10% of the active workforce.
- A major deterrent for young entrants is the health toll; welders are 100 times more likely to have a workplace injury than the average general worker.
- The American Welding Society projects that welding occupations will need to fill an average of 80,000 openings annually between 2025 and 2029.<sup>31</sup>



Source: Path Robotics; American Welding Society

To keep production lines running, companies are deploying autonomous welding cell systems that use AI and sensing technology to execute welds with less manual programming.<sup>32</sup> Besides allowing older master welders to oversee production without the grueling physical toll, robotic welding can also create technical roles attractive to younger workers, with one leading developer reporting that its field service technicians average 39 years old, 16 years younger than today's industry average welder.<sup>33</sup>

<sup>31</sup> [Shining a Light on the Welding Workforce](#), American Welding Society (last accessed 2026).

<sup>32</sup> [Intelligent Welding Cells](#), Path Robotics (last accessed 2026).

<sup>33</sup> SCSP Staff Engagement with Path Robotics (August 2026).

## Manufacturing Has Lost the Wage Premium That Once Attracted Workers

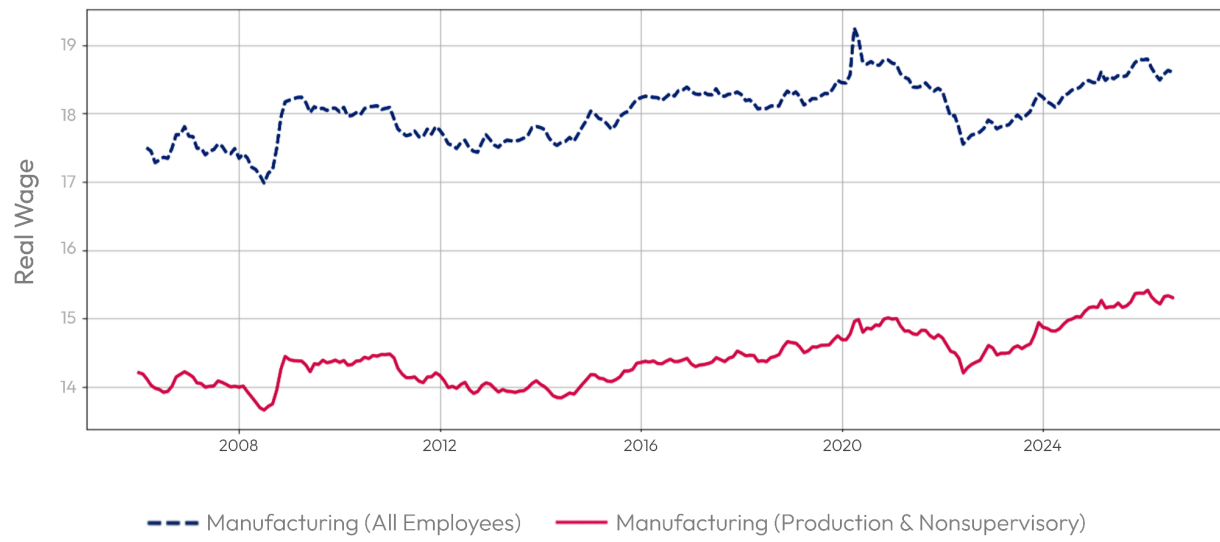
Manufacturing's workforce is aging out faster than replacements are arriving, creating an urgent need to hire new talent. Understanding why young people are choosing other careers instead requires examining the worker value proposition: the full mix of pay, security, and status a job offers relative to its alternatives. This section focuses on compensation, and specifically how manufacturing pay has changed relative to other industries over time. Sixty percent of manufacturers cite core production workers—operators, assemblers, and packaging workers—as a key hiring need, second only to skilled trades. These roles form the entry pipeline for skilled trades and robotics-enabled work, and because they generally require only a high school diploma, their compensation offers the clearest test of manufacturing's competitiveness for talent.

For decades, the manufacturing sector offered a consistent wage premium over industries with comparably skilled workforces. Research finds that this advantage has declined substantially after 1979 and had largely disappeared for production workers by 2018.<sup>34</sup> Yet, aggregate manufacturing wage figures include highly paid nonproduction workers—managers, engineers, and administrative staff—alongside frontline workers, which overstates what a typical factory-floor job actually pays. Comparing all manufacturing employees with production and nonsupervisory employees shows how these averages differ (Figure 7).

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<sup>34</sup> Joel A Elvery & Julianne Dunn, [Manufacturing Wage Premiums Have Diverged between Production and Nonproduction Workers](#), Federal Reserve Bank of Cleveland (2021).

**Figure 7 | Real Hourly Wages: Manufacturing Comparison**

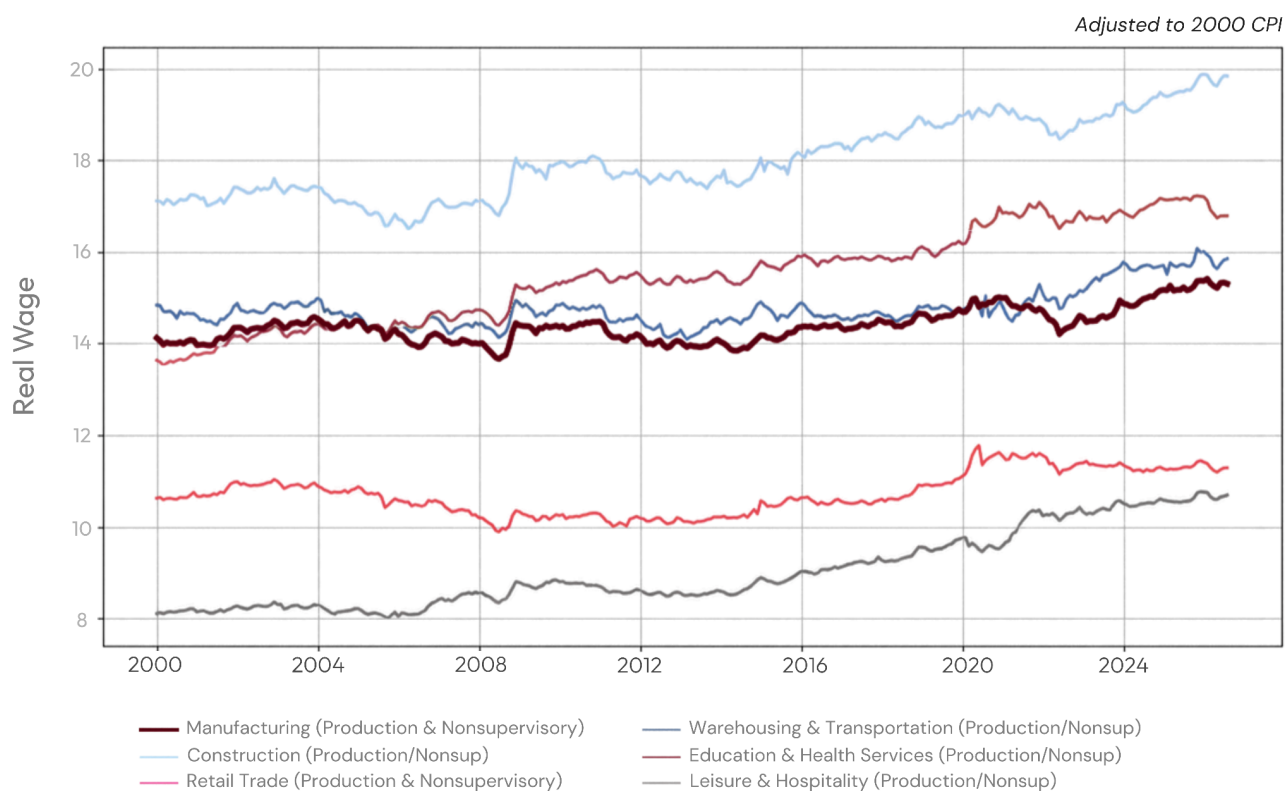


Source: Bureau of Labor Statistics<sup>35</sup>

Furthermore, isolating production and nonsupervisory compensation reveals a clear trajectory of manufacturing wages trailing behind broader economic benchmarks. Around 2005, average frontline manufacturing wages dropped below those in warehousing, transportation, and education and health services (Figure 8).

<sup>35</sup> [Average Hourly Earnings of All Employees, Manufacturing](#), U.S. Bureau of Labor Statistics (last accessed 2026).

**Figure 8 | Real Hourly Wages by Sector Over Time**



Source: Bureau of Labor Statistics<sup>36</sup>

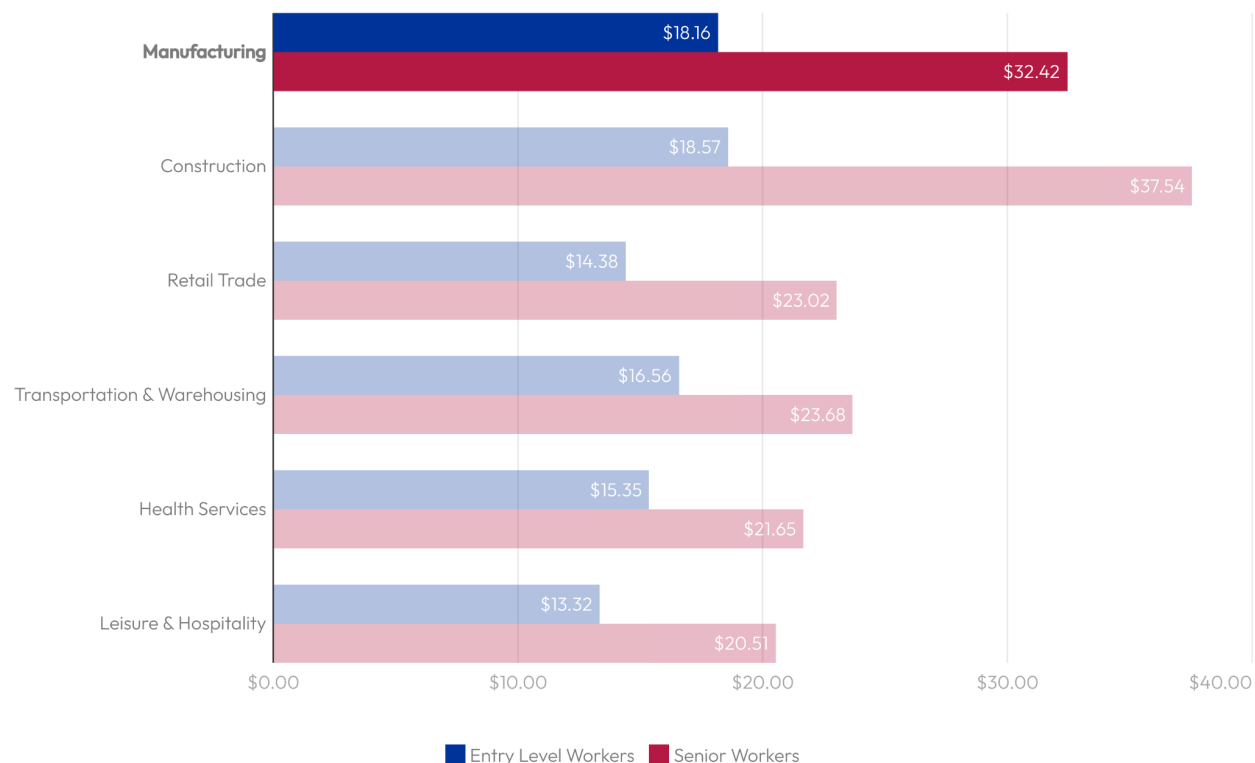
To accurately compare base compensation across key economic sectors, the Commission’s methodology bridges Current Employment Statistics (CES) with Occupational Employment and Wage Statistics (OEWS) data. This approach filters out managerial skew by mapping production cohorts to specific occupational proxies that share comparably low entry barriers, typically requiring only a high school diploma or equivalent, including assemblers, construction laborers, retail salespersons, warehouse stockers, and healthcare support workers. This approach also excludes skilled trades, such as machinists, welders, and industrial machinery mechanics, since these roles typically require postsecondary training or apprenticeship beyond a high school diploma.

Evaluating May 2025 OEWS hourly wage distributions demonstrates the current earnings gap across two distinct experience milestones: the lower- and upper-end wage

<sup>36</sup> [Current Employment Statistics: Average Hourly Earnings of Production and Nonsupervisory Employees by Industry](#), U.S. Bureau of Labor Statistics Public Data API (last accessed 2026).

benchmarks—the 25th percentile for entry-level workers and the 90th percentile for experienced workers (Figure 9).

**Figure 9 | Hourly Wages for Workers in Production and Nonsupervisory Roles (2025)**



Source: Bureau of Labor Statistics<sup>37</sup>

The drivers behind the collapse of the manufacturing wage premium are multifaceted and rooted in broad structural shifts in the labor market. Federal Reserve research attributes a substantial share of this vanished premium to deunionization over the last three decades.<sup>38</sup> Further research finds that an increased reliance on temporary staffing agencies has lowered labor costs while eroding the sector's historical pay advantage, explaining more than 10% of the aggregate employment decline in core manufacturing jobs between 1997 and 2018.<sup>39</sup>

<sup>37</sup> [May 2025 National Industry-Specific Occupational Employment and Wage Estimates](#), U.S. Bureau of Labor Statistics, Occupational Employment and Wage Statistics (2026).

<sup>38</sup> Kimberly Bayard, et al., [Are Manufacturing Jobs Still Good Jobs? An Exploration of the Manufacturing Wage Premium](#), U.S. Federal Reserve (2022).

<sup>39</sup> Lawrence Mishel, [Yes, Manufacturing Still Provides a Pay Advantage, But Staffing Firm Outsourcing is Eroding It](#), Economic Policy Institute (2018).

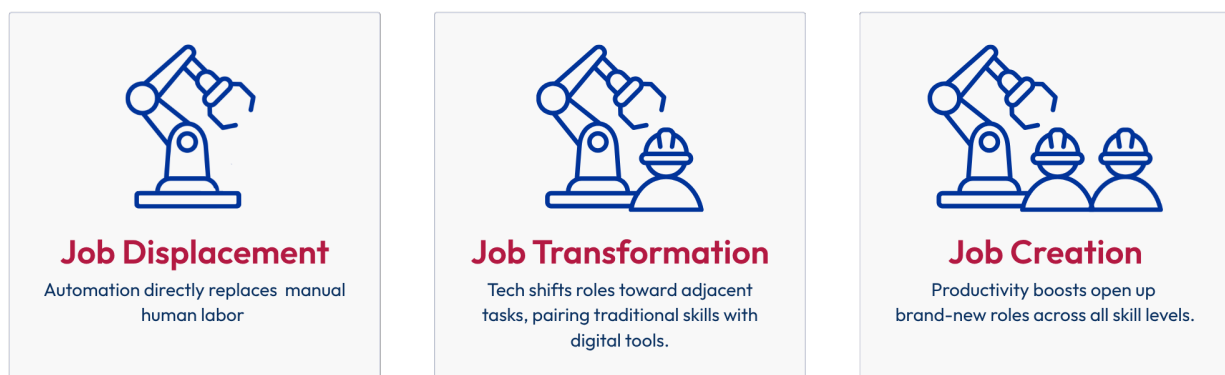
Ultimately, the disappearance of the wage premium, alongside broader, harder-to-quantify concerns about industry prestige, job security, and the physical demand of the work, has fundamentally degraded the worker value proposition in manufacturing. Recognizing this loss of competitive advantage is essential to understanding and, ultimately, addressing the root causes of the manufacturing workforce shortage.

However, discussions of labor shortages must be contextualized alongside the public concern regarding worker displacement by robotics. While robotics can alleviate critical staffing gaps and reduce physical strain on workers, the overall impact hinges on the conditions of its implementation.

## **Finding 4: The effects of robotics on employment are ambiguous and not predetermined.**

The effects of automation on employment are shaped by three forces that operate simultaneously: job displacement, job transformation (complementary job redesign), and new job creation. The net employment effect in any given firm, occupation, or region depends on the relative magnitude of each, which in turn depends on the pace of adoption, the task structure of the work being automated, and the policy environment surrounding the transition. This is why robotics adoption produces starkly different labor-related outcomes across manufacturing subsectors and geographies rather than a uniform trend in one direction.

**Figure 10 | The Impact of Robotics on Employment**



## Displacement

Displacement occurs when automation substitutes capital for labor, replacing human work hours with machine operating hours for the same tasks. In manufacturing, this has historically taken the form of deploying robotics to take over so-called dull, dirty, and dangerous jobs. These are roles dominated by routine, repetitive, and physically punishing tasks that frequently expose workers to ergonomic strain or hazardous environments. Examples include repetitive assembly, waste sorting, warehouse box handling, manual welding, handling hazardous materials, and working in confined spaces—in these cases, automation often acts as an occupational health and safety upgrade as much as a productivity driver.<sup>40</sup>

Displacement remains a prominent public concern, but it is not the only outcome of robotics adoption. When deployment is paired with training and worker participation, firms can create new roles, move workers to higher-value tasks, and manage some headcount changes through natural attrition. In factories with persistent vacancies, robotics can also cover work that employers are unable to staff. These possibilities do not eliminate displacement risk; outcomes vary by firm, task, and labor market.<sup>41</sup>

## Job Transformation

The second force operates alongside displacement through a mechanism known as the productivity effect. As advanced robotics absorbs the repetitive, physically demanding, or hazardous components of a job, the value of human labor in non-automated tasks increases. The remaining role is frequently redesigned to focus on the non-automated tasks, with robots serving as tools to make workers more productive.<sup>42</sup> For instance, data from one leading autonomous welding manufacturer shows that a welder trained to operate a specialized robotic cell can achieve up to five times the output of a traditional manual welder.<sup>43</sup>

In practice, a machine operator's daily responsibilities frequently shift away from manual part placement toward higher-level robot supervision, system calibration, and error troubleshooting. Worker-centered robotics presents opportunities for human-in-

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<sup>40</sup> [How Robots Are Taking on the Dirty, Dangerous, and Dull Jobs](#), Association for Advancing Automation (2019).

<sup>41</sup> [Robots Aren't Taking Jobs: Uncovering the Real Crisis in Manufacturing](#), Association for Advancing Automation (2026).

<sup>42</sup> [Robots Aren't Taking Jobs: Uncovering the Real Crisis in Manufacturing](#), Association for Advancing Automation (2026).

<sup>43</sup> SCSP Staff Engagement with Path Robotics (August 2026).

the-loop production, such as the deployment of collaborative robots (cobots) that shop-floor workers can directly program and adjust. Manufacturers with models like the Toyota Production System have demonstrated that leveraging frontline workers’ hands-on knowledge to manage automated systems leads to faster error detection, highly flexible production lines, and superior output quality.<sup>44</sup> These redesigned roles demand analytical capabilities different from those required by the displaced physical tasks, so adaptable training pathways are crucial.

### New Job Creation

The third force is the reinstatement effect: new technology creates new tasks that require human labor and, in turn, new jobs. In manufacturing, the reinstatement effect materializes through the growth of robotics-adjacent roles that did not exist prior to automation, such as specialized technician-level roles, including robot maintenance specialists, systems integrators, and industrial programmers.

Figure 11 | Robotics-Adjacent Roles

| Role                | Common Job Titles                                                                                                            | Education Required                                                                                | National Median Base Salary |
|---------------------|------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-----------------------------|
| Robotics Technician | Robot Operator<br>Entry Level Robotics<br>Assembly Operator                                                                  | High School Diploma or GED<br>Post-Secondary Certificate<br>or Associate's Degree                 | \$59,299                    |
| Robotics Specialist | Robotics Specialist<br>Robotics Engineer<br>Mechatronics Engineer<br>Automation Engineer<br>Robotic Systems Engineer         | Associate's Degree (with Career Advancement)<br>Bachelor's Degree<br>Sometimes Master's Preferred | \$124,827                   |
| Robotics Integrator | Robotics Integrator<br>Robotic Integration Design Engineer<br>Robotics Software Integrator<br>Advanced Industrial Integrator | Bachelor's Degree<br>Sometimes Master's Preferred                                                 | \$132,750                   |

Source: Robotics Career, The ARM Institute<sup>45</sup>

Beyond the factory floor, this technological shift drives demand for a highly skilled technical workforce. According to research from the World Economic Forum, industrial automation is accelerating the need for specialized roles such as robotics engineers, system designers, and digital transformation managers who oversee automation transformations and translate factory data into operational insights.<sup>46</sup>

<sup>44</sup> [Toyota Production System](#), Toyota (last accessed 2026).  
<sup>45</sup> [RoboticsCareer.org](#), RoboticsCareer.org (last accessed 2026).  
<sup>46</sup> [The Future of Jobs Report 2023](#), World Economic Forum at 21-24 (2023).

## The Net Employment Outcomes

Taken together, job displacement, complementary job redesign, and new job creation mean that the employment effect of robotics in any given manufacturing context remains an open question. Where displacement outpaces job redesign and creation, net employment can be negative. However, this displacement effect is counteracted by a productivity effect: automation lowers manufacturing costs, allowing firms to expand output, enter new markets, and increase demand for non-automated, complementary tasks. At a broader scale, these cost reductions could enhance U.S. competitiveness, encouraging capital investment in new domestic factory buildouts and industrial facilities that generate expanded job opportunities and regional economic growth. Whether net employment in any given manufacturing context expands or contracts ultimately depends on whether job creation and task redesign keep pace with initial task displacement.

The overall employment impact of industrial robotics remains unsettled in the empirical literature. The primary baseline for displacement comes from a foundational U.S. study analyzing commuting zones from 1990 to 2007, which estimated that each additional robot per thousand workers reduced aggregate national employment by roughly 3.3 jobs.<sup>47</sup> In contrast, European studies over comparable periods find different outcomes: one study found zero net job losses across 17 industrialized countries, while another found a net positive employment effect across 16 EU economies, mainly driven by higher job stability.<sup>48</sup> These contrasting results demonstrate that employment outcomes are neither fixed nor predetermined, but depend heavily on institutional context and underlying research assumptions.

That ambiguity matters, because aggregate employment data cannot on its own isolate the effect of automation. U.S. manufacturing employment fell by roughly 290,000 between December 2023 and a low in December 2025, from 12.87 million to 12.58 million—a decline driven largely by cyclical and policy factors rather than technological displacement. Payrolls have recovered 72,000 since, to 12.65 million in September 2026, though they remain below their February 2020 level.<sup>49</sup> Employer demand is

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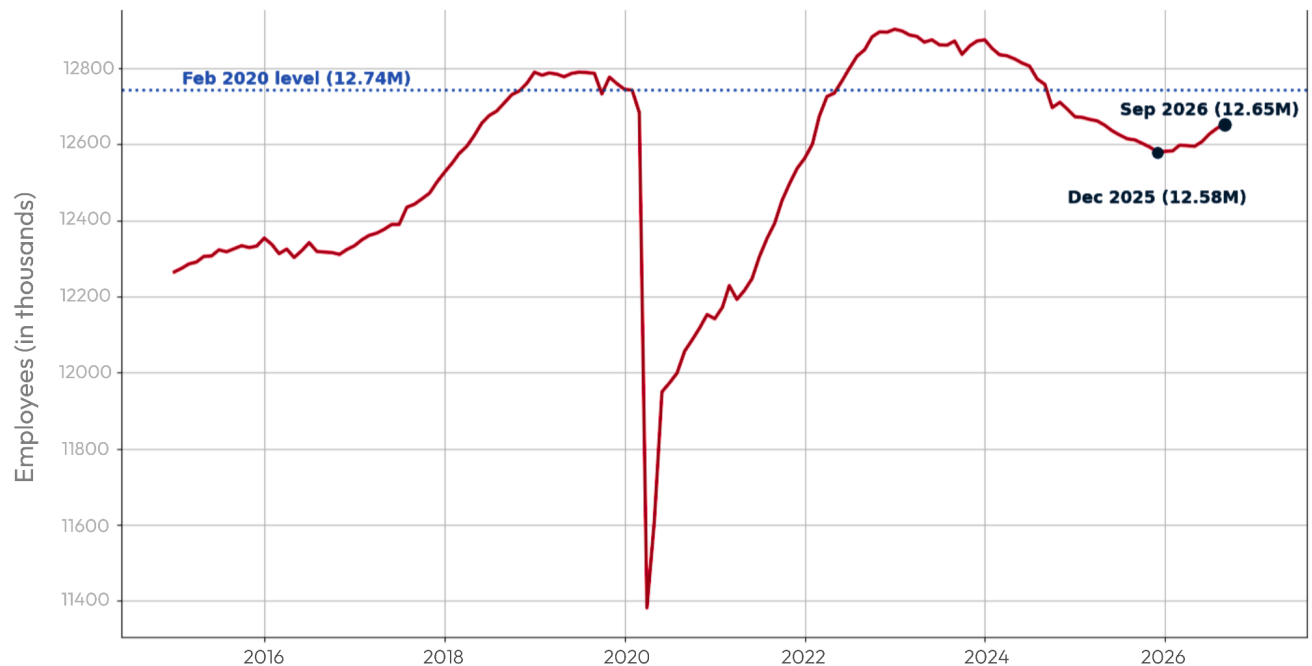
<sup>47</sup> Daron Acemoglu & Pascual Restrepo, [Robots and Jobs: Evidence from US Labor Markets](#), Journal of Political Economy (2020).

<sup>48</sup> Georg Graetz & Guy Michaels, [Robots at Work](#), The Review of Economics and Statistics (2018); Ronald Bachmann, et al., [The Impact of Robots on Labour Market Transitions in Europe](#), Structural Change and Economic Dynamics (2024).

<sup>49</sup> [All Employees, Manufacturing \(CES3000000001\)](#), U.S. Bureau of Labor Statistics (2026).

running ahead of hiring: manufacturing job openings reached 522,000 in August 2026, up from 416,000 a year earlier.<sup>50</sup> Whether that demand converts into employment depends on credentialing and training pathways matching employer needs and scaling at the pace demand requires.

**Figure 11 | Total U.S. Manufacturing Employment (2015-2026)**



Source: Bureau of Labor Statistics<sup>51</sup>

## **Finding 5: Labor shortages and skills misalignment limit manufacturing at scale and robotics deployment.**

While automation has the potential to reinvigorate and expand the manufacturing base, a persistent mismatch in skills currently constrains its deployment. Manufacturers simply do not have the technicians to integrate, operate, and maintain robotic systems.

<sup>50</sup> [Job Openings and Labor Turnover — August 2026, Table 1: Job Openings Levels and Rates by Industry and Region](#); [Job Openings and Labor Turnover — August 2026, Table 2: Hires Levels and Rates by Industry and Region](#), U.S. Department of Labor, Bureau of Labor Statistics (2026).

<sup>51</sup> [Current Employment Statistics: All Employees, Manufacturing, Seasonally Adjusted](#), U.S. Bureau of Labor Statistics (2026).

A critical driver of the manufacturing workforce deficit is uncertainty about the specific skills employers require. As both the manufacturing industry and robotics capabilities evolve, the skills needed to integrate automation effectively are shifting quickly, producing weak and conflicting market signals for educational institutions to adapt curricula. To address these gaps, industry consortia such as the ARM Institute are working to define and standardize "adaptive skills," including complex problem-solving and systems-level understanding.<sup>52</sup> Several organizations and states have adopted the ARM Institute's definitions, and its RoboticsCareer.org platform brings competencies, training, credentialing, and job-matching data together in one place.<sup>53</sup> Many employers still write job descriptions and set hiring requirements without reference to a common standard, leaving educational institutions disconnected from actual factory-floor requirements.<sup>54</sup> As a result, credentials and training pathways for manufacturing workers have become highly fragmented across institutions, job functions, and certifying bodies.

The World Economic Forum reports that advanced manufacturing sectors—such as aerospace, chemicals, and electronics—face significant workforce transformation, with employers expecting nearly two-thirds of core skills to evolve within five years toward digital fluency and complex data analysis alongside traditional mechanical expertise.<sup>55</sup> Globally, industry leaders foresee a need to upskill 29% of their current workforce and reskill 15% into new roles, while more than half plan to target diverse talent pools to address labor shortages.<sup>56</sup>

Domestically, the National Skills Coalition initially estimated that the Inflation Reduction Act, the CHIPS and Science Act, and the Infrastructure Investment and Jobs Act would generate 230,000 new manufacturing jobs annually across 48 occupations.<sup>57</sup> While recent policy rollbacks under the One Big Beautiful Bill Act (OBBBA) and Department of Energy award cancellations have narrowed those gains—reducing that projection by

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<sup>52</sup> [Empowering the Workforce of Today & Building the Workforce of the Future](#), ARM Institute (last accessed 2026).

<sup>53</sup> John Zappa, [Revolutionizing Manufacturing with Advanced Robotics](#), RoboticsCareer.org (2024).

<sup>54</sup> Megan Andrew, et al., [An Analysis of Education and Training Programs in Advanced Manufacturing Using Robotics](#), RAND (2020).

<sup>55</sup> [The Future of Jobs Report 2025](#), World Economic Forum at 41 (2025).

<sup>56</sup> [The Future of Jobs Report 2025](#), World Economic Forum at 84 (2025).

<sup>57</sup> [Unprecedented Opportunity: Meeting the Workforce Demands of New Clean Energy, Manufacturing, and Infrastructure Investments](#), National Skills Coalition (2024).

47,000 expected manufacturing jobs—acute talent shortages persist in manufacturing.<sup>58</sup>

**U.S. Apprenticeships Have Limited Reach and Must Adapt to Changing Robotics Skills**

Historically, apprenticeships were designed to level the playing field, providing workers with the baseline skills and practical knowledge necessary to succeed. Jobs for the Future’s blueprint to Modernize and Expand Apprenticeship Nationwide identifies an 88% increase in the number of apprentices in the United States since 2015; however, apprentices still make up only 0.3% of the U.S. workforce as of 2025.<sup>59</sup> When compared to international peers, the United States trails significantly in utilizing apprenticeships as a primary workforce development tool:

Figure 12 | Apprentices by Country

| Country                                                                                            | Apprentices (% of Working Age) |
|----------------------------------------------------------------------------------------------------|--------------------------------|
|  United States  | 0.30%                          |
|  Switzerland    | 3.60%                          |
|  Germany        | 2.30%                          |
|  Canada         | 1.80%                          |
|  Australia      | 1.80%                          |
|  United Kingdom | 1.70%                          |

Source: Third Way <sup>60</sup>

More specifically, there are between 95,000 and 97,500 registered apprentices in manufacturing and advanced manufacturing, yielding an active in-training ratio of

<sup>58</sup> Bait and Switch: The Impacts of Trump Administration Policies at the Intersection of Clean Energy, Manufacturing, and Labor, BlueGreen Alliance (2026).  
<sup>59</sup> Taylor Maag, et al., Policy Blueprint to Modernize and Expand Apprenticeship Nationwide, Jobs for the Future (2025).  
<sup>60</sup> Curran McSwigan & Frank Avery, What Five Countries Can Teach America About Apprenticeships, Third Way (2025).

approximately 0.7% to 0.8%.<sup>61</sup> Importantly, this metric only accounts for formal registered programs. As a broader landscape of alternative training models continues to develop alongside them, evaluating these emerging pathways against national competitiveness goals requires a baseline understanding of the structural trade-offs between traditional governance and modern training frameworks.

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<sup>61</sup> [Advanced Manufacturing](#), U.S. Department of Labor, Office of Apprenticeship (2025).

### Figure 13 | Strategic Trade-Offs in U.S. Apprenticeship Governance

**Registered Apprenticeship Programs:** Formally validated by the U.S. Department of Labor (DOL) or State Apprenticeship Agencies.

- *Strategic Advantage:* Provides high regulatory quality control, mandatory progressive wage scale increases, national credential portability across various employers, and access to federal formula funds (e.g., WIOA).
- *Friction:* Administrative requirements and multi-year curriculum approval cycles create lag times that fail to keep pace with rapid robotics software iterations.

**Unregistered & Industry-Led Pathways:** Employer- and consortium-owned internal training tracks (e.g., corporate bootcamps, vendor certificates).

- *Strategic Advantage:* Maximum speed-to-deployment, real-time alignment with proprietary factory machinery, and agile curriculum updates.
- *Friction:* Results in non-portable credentials, risks worker exploitation due to unverified labor standards, and remains ineligible for most public workforce dollars.

### **Delivery Structures:**

Program execution across both registered and unregistered systems relies on three distinct structural delivery mechanisms.

1. **Time-Based:** Measures skill acquisition through fixed hours in training. Registered apprenticeships require a minimum of 2,000 On-the-Job Training (OJT) hours and 144 Related Technical Instruction (RTI) hours per year.
2. **Competency-Based (demonstrated mastery):** Replaces time tracking with direct evaluation of demonstrated technical mastery. Trainees advance as soon as they pass standardized competency check-offs
3. **Hybrid Structures:** Combines a flexible range of OJT hours with mandatory milestone competency evaluations at each phase.

While traditional apprenticeships excel at building a deep foundational baseline, they face a severe timing constraint. The traditional multi-year model struggles to adapt quickly to the rapid changes of Industry 4.0—the integration of automated systems, IoT, and data-driven production on factory floors. Redesigning legacy registered apprenticeship standards is often expensive and time-consuming, as updating federally approved work schedules and re-accrediting curricula through state boards can take up to two years.<sup>62</sup> Furthermore, instructors frequently lack the mastery of cutting-edge technology to teach these rapidly evolving digital skills.

To bridge the immediate skills gap on the factory floor, the broader workforce ecosystem—spanning educators, employers, credentialing bodies, and policymakers—is shifting toward specialized agile micro-credentials and formal “new collar” pathways, which target high-skill technical positions that sit between manual assembly and traditional four-year engineering.

### **Adaptation to Robotics: Agile Credentials and Partnerships**

In response to these pressures, workforce development is shifting toward short-term, adaptable training models and nontraditional skill pathways. Leading this shift is Manufacturing USA, a national network of 18 manufacturing and innovation centers that operate as public-private partnerships, allowing workers and technologies to shift across sectors through shared research and workforce development standards.<sup>63</sup> The emerging training pathways are grouped into formal credential pathways for new occupational categories and short-term training pathways for agile skill acquisition. Across both, employers need confidence that training translates into job-ready skills. Endorsement programs, like one led by the ARM Institute, can address this. These programs evaluate and recognize effective robotics and AI training programs for manufacturing careers.

Formal credential pathways aimed at training “new collar” talent typically take 18–24 months, result in a portable credential, and rely heavily on community colleges for regional accreditation, and on industry for state-of-the-art equipment labs.<sup>64</sup> Two emerging occupations illustrate this pathway:

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<sup>62</sup> Taylor Maag, et al., [Policy Blueprint to Modernize and Expand Apprenticeship Nationwide](#), Jobs for the Future (2025).

<sup>63</sup> [Manufacturing Workforce Development](#), Manufacturing USA (last accessed 2026).

<sup>64</sup> [Robotics and Automation Technician](#), Pennsylvania College of Technology (last accessed 2026).

- **The Automation Technician** is a hybrid role: part mechanic, part IT specialist. Apprentices work paid, part-time hours at a manufacturing facility while taking classes one or two days a week at a local community college or skill center. The curriculum bridges legacy machinery with next-generation technologies in areas such as programmable logic controller (PLC) programming, robotic cell troubleshooting, fluid power dynamics, and smart-sensor integration. Organizations like AJAC (Aerospace Joint Apprenticeship Committee) in Washington State have pioneered this 16-to-24-month (roughly 2,000-hour) model.<sup>65</sup>
- **The Technologist** sits between a university-trained mechanical engineer and a floor-level assembly worker. This occupation pathway focuses on applied engineering—programming the CNC machines, controlling the robots, and designing the actual plant layouts to build the product efficiently.<sup>66</sup>

Agile certificates and corporate partnerships provide shorter-term pathways built for rapid deployment. Rather than conferring full degrees, these programs issue targeted certificates and micro-credentials to quickly upskill existing production workers or train new hires on specific machinery in weeks or months:

- **Micro-credentials and bootcamps:** Instead of a multi-year degree, micro-credentials offer rapid, highly targeted training in specific technical competencies, such as robotic vision systems and predictive maintenance algorithms.
- **Accelerated corporate training programs:** Private industry is also bypassing the registered apprenticeship model through direct public-private partnerships. Tesla’s START Manufacturing Program operates as a 14-week intensive “earn while you learn” bootcamp that condenses years of electromechanical training in advanced robotics, programmable logic controllers, and automated systems, partnered with Austin Community College and Diablo Valley College. Similarly, the Path Robotics Advanced Manufacturing AI Apprenticeship Program provides a specialized AI apprenticeship program to upskill operators on advanced automated systems in real time.

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<sup>65</sup> [Youth Apprenticeship](#), Aerospace Joint Apprenticeship Committee (last accessed 2026).

<sup>66</sup> John Liu & William B. Bonvillian, [The Technologist](#), *Issues in Science and Technology* (2024); [From Technician to Technologist](#), Massachusetts Institute of Technology (last accessed 2026).

This pressure to adapt to the digital transformation of manufacturing is a global phenomenon; German educational authorities and industrial bodies have modernized traditional mechatronics apprenticeships, requiring state-certified programs to incorporate competencies in digital twins, predictive maintenance, and robotics programming.<sup>67</sup>

## Policy Shifts

To support these new pathways, targeted policy shifts and funding mechanisms are emerging to reduce the barriers facing both employers and workers. These barriers include the upfront cost of establishing training programs, the cost to individuals of pursuing short-term credentials, and the weak awareness of manufacturing careers among young people.

- **The American Manufacturing Apprenticeship Incentive Fund** was established to help employers overcome upfront training costs. The U.S. Department of Labor recently awarded a four-year, \$35.8 million in cooperative agreement administered by the State of Arkansas. The fund uses a pay-for-performance model and provides a \$3,500 payout to employers for every registered apprentice who completes a 90-day probationary period. These incentives offset immediate onboarding and wage expenses across more than 120 advanced manufacturing occupations, including semiconductors, aerospace, robotics, and nuclear energy.<sup>68</sup>
- **Workforce Pell Grants: Unlocking Short-Term Training.** Historically, federal financial aid has favored traditional two- or four-year degree tracks. Enacted under the OBBBA, federal Pell Grants can be applied directly to short-term workforce training programs for the first time. Starting July 1, 2026, funds can be applied to short-term programs lasting between eight and 15 weeks (150 to 599 instructional hours).<sup>69</sup>
- **BuildFreedom.US: Building Awareness of Manufacturing Careers.** The Department of War recently launched BuildFreedom.US, a coalition of

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<sup>67</sup> [Industry 4.0 Ausbildung: Germany's €3,800 Smart Manufacturing Career Revolution](#), GoAusbildung (2025).

<sup>68</sup> [American Manufacturing Apprenticeship Incentive Fund](#), Arkansas Office of Skills Development (last accessed 2026); [American Manufacturing Apprenticeship Incentive Fund](#), North Carolina Community Colleges (2026).

<sup>69</sup> [Tesla Manufacturing at ACC](#), Austin Community College (last accessed 2026).

government, industry, and education partners to raise awareness of skilled trades and manufacturing careers among students and young adults. The initiative includes a \$10 million investment in skilled-trades scholarships. Though still in its early stages, it is one of the most significant federal efforts in years to attract young people to manufacturing.<sup>70</sup>

## STEM Pipeline

An insufficient STEM pipeline further threatens long-term U.S. leadership in robotics innovation. This weakness reflects a structural misalignment between traditional academia and market needs, as standard programs routinely fail to ground theoretical mathematics and engineering principles in hands-on, real-world manufacturing environments. Compounding the issue is decades of production offshoring, which stripped the domestic workforce of critical hardware engineering knowledge—a domain best mastered through physical production at scale.<sup>71</sup>

At the K-12 level, the talent pipeline weakens early. U.S. students begin falling behind their international peers in math as early as elementary school: between 2019 and 2023, U.S. fourth-grade math scores fell 18 points and eighth-grade scores fell 27 points on the Trends in International Mathematics and Science Study (TIMSS) international assessment, while East Asian education systems led both grades.<sup>72</sup> The pipeline also suffers from a steep drop-off in student engagement. National enrollment data show that while 57% of U.S. high schools offer computer science courses, only 5.8% of high school students actually enroll, illustrating the difficulty of converting course availability into student participation.<sup>73</sup> Extensive research by the National Research Council suggests that student persistence in technical pathways increases significantly when abstract engineering and math concepts are anchored in hands-on, problem-based learning tied to real-world industrial applications.<sup>74</sup> A study of high school participation in applied hands-on engineering programs found an increase in the likelihood of declaring a postsecondary STEM major by up to 10 percentage points—effectively

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<sup>70</sup> [DOW Launches BuildFreedom.US, Announces \\$10M Skilled Trades Investment With Mike Rowe and Forge the Next-Generation Industrial Workforce](#), U.S. Department of War (2026); [We Need You to Rebuild America](#), BuildFreedom.US (last accessed 2026).

<sup>71</sup> Elisabeth B. Reynolds & Hiram Samel, [Invented in America, Scaled Up Overseas](#), The American Society of Mechanical Engineers (2019).

<sup>72</sup> [Mathematics Scores of U.S. Fourth- and Eighth-Graders Decline on International Mathematics and Science Assessment](#), U.S. Department of Education, Institute of Education Sciences (2024).

<sup>73</sup> [State of AI + CS Education](#), Code Advocacy Coalition (2025).

<sup>74</sup> Margaret Honey, et al., [STEM Integration in K-12 Education](#), National Academies (2014).

doubling the baseline technical declaration rate compared to academically matched peers.<sup>75</sup> Yet research suggests that much of students' robotics exposure bears little relation to industrial work, with many programs centered on educational kits or competition robots rather than factory-floor systems. While cost is a factor, even with low-cost robots, students can work on challenges that mimic factory floor applications.<sup>76</sup>

At the higher education level, the sequencing of foundational coursework can pose bottlenecks to scaling STEM careers. Mathematics is the essential language of robotics and engineering, but when students must complete a traditional, procedure-heavy calculus sequence before applying math to engineering problems, many potentially capable students are filtered out.<sup>77</sup> In response, leading institutions have taken an application-first approach to engineering education to make it more accessible and immediately relevant to industry applications. Wright State University replaced its calculus prerequisite with an applied engineering-math course, and students who took it were more than twice as likely to earn an engineering degree.<sup>78</sup> The University of Michigan developed a Robotics 101 course that teaches linear algebra through robotics problems with no calculus prerequisite, an approach designed, in its creators' words, to "invite in rather than 'weed out'" students.<sup>79</sup>

## Innovation and R&D Talent

Beyond undergraduate education, the pinnacle of the university STEM pipeline for advanced R&D remains highly vulnerable to two structural weaknesses: the geographic separation of engineering from production, and a shrinking domestic talent pipeline in graduate programs. First, advanced robotics R&D is deeply intertwined with the physical components of manufacturing, so severing R&D from production degrades a

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<sup>75</sup> Takako Nami, et al., [Project Lead the Way: Impacts of a High School Applied STEM Program on Early Post-Secondary Outcomes](#), Journal of Research on Educational Effectiveness (2025).

<sup>76</sup> Greg J. Strimel, et al., [The Next Generation for Manufacturing Competitiveness?: Investigating the Influence of Industry-Driven Outreach on Children's Career Perceptions](#), International Journal of Technology and Design Education at 14 (2020).

<sup>77</sup> Jenna Carpenter, et al., [Mathematics as a Gateway, Not a Barrier: Reimagining Engineering Preparation for the 21st Century](#), Education Sciences (2026).

<sup>78</sup> Nathan W. Klingbeil & Anthony Bourne, [A National Model for Engineering Mathematics Education: Longitudinal Impact at Wright State University](#), American Society for Engineering Education at 23.76.1, 23.76.6 (2013).

<sup>79</sup> [‘Solving for equity’: A Michigan Robotics course flips the script on engineering ed](#), University of Michigan (2021).

nation's innovation pipeline.<sup>80</sup> As noted above, offshoring costs the United States the hardware know-how that is learned only through production at scale. Second, the advanced engineering pipeline that does remain in the United States frequently faces instability due to its demographic composition. With fewer domestic students progressing into advanced robotics-specific fields, the sector is heavily reliant on international students that are visa-dependent. Rapid and unpredictable changes to immigration policies generate a volatile environment for retaining highly trained graduates, who may then move to other countries.

## **Training Workers for Automation**

Manufacturing is facing severe worker shortages. Older workers are retiring and uncompetitive wages mean younger workers are not sufficient to replace them. Where those conditions hold, robotics is less a job-taking threat than a means of keeping factories open. As Finding 4 sets out, that outcome is not automatic: it depends on the pace of adoption, the task structure of the work being automated, and whether training pathways scale with deployment.

Ultimately, manufacturers cannot scale automation without a modernized, agile credentialing system, and the nation cannot sustain its technological edge without a robust, application-driven STEM pipeline securing the next generation of engineers and technicians.

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<sup>80</sup> Elisabeth B. Reynolds & Hiram Samel, [Invented in America, Scaled Up Overseas](#), The American Society of Mechanical Engineers (2019).

# Adoption at Scale: New Capabilities Are Expanding the Market, but Persistent Barriers Hold Manufacturers Back

Robots can be used to automate dangerous and undesirable tasks, improve product quality and reliability, increase throughput and capacity, offset labor shortages, and create competitive advantages. However, U.S. deployment reveals a substantial gap.

In 2021, according to U.S. Census Bureau data, only 12.1% of manufacturing plants reported using robots.<sup>81</sup> Annual installations of industrial robots peaked in the United States at 40,000 units in 2022, or 7% of the global total, and fell to 6.3% in 2024. Preliminary numbers indicate a rebound to 38,400 in 2025.<sup>82</sup> The deployment gap is also visible in the U.S. operational stock, which represents 8.3% of the global total as of 2024.<sup>83</sup>

By comparison, under its Made in China 2025 initiative launched in 2015, China set a goal of 1.8 million operational robots by 2025. This goal was met early in 2024 when China's operational stock surpassed 2 million, more than five times the U.S. total.<sup>84</sup> China continues to prioritize robotics in its most recent Five-Year Plan.<sup>85</sup>

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<sup>81</sup> [Annual Survey of Manufacturers Industrial Robotics Equipment: 2018-2021](#), United States Census Bureau (2025).

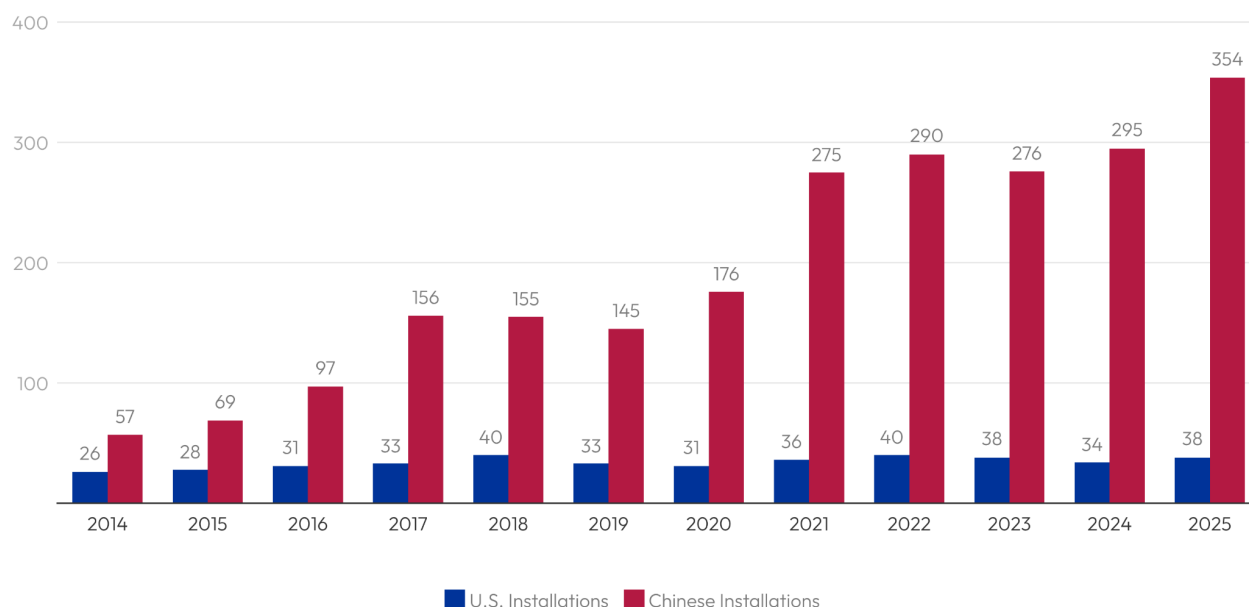
<sup>82</sup> [World Robotics Report 2026](#), International Federation of Robotics (2026); [U.S. Robot Industry Returns to Double Digit Growth](#), International Federation of Robotics (2026).

<sup>83</sup> [World Robotics Report 2025](#), International Federation of Robotics (2025).

<sup>84</sup> Hugh Grant-Chapman, et al., [Is China Leading the Robotics Revolution](#), CSIS China Power Project (2026).

<sup>85</sup> [China Makes AI-Powered Robots Core of National Strategy](#), International Federation of Robotics (2026).

**Figure 14 | U.S. and Chinese Industrial Robot Installations (Thousands of Robots)**



Source: International Federation of Robotics<sup>86</sup>

This under-adoption is shaped by the structural makeup of American industry. U.S. manufacturing consists of a small number of large firms and a vast network of SMMs. SMMs account for approximately 95% of all U.S. manufacturing firms, and are often crucial sub-tier suppliers that maintain key domestic capabilities for defense manufacturing, yet they continue to struggle with robotics adoption.<sup>87</sup>

To analyze this shortfall, the Commission evaluated both the technological shifts expanding the range of viable applications and the persistent operational barriers holding firms back.

<sup>86</sup> [World Robotics Report 2026](#), International Federation of Robotics (2026).

<sup>87</sup> [Facts About Small Business: Manufacturing Statistics 2025](#), U.S. Small Business Administration (2025); [All Employees, Manufacturing](#), Federal Reserve Bank of St. Louis (2026); Farooq Mitha, [Why Small Businesses are Essential to U.S. National Security](#), U.S. Department of War (2021).

## **Finding 6: The industrial robotics landscape is undergoing a transformation in deployment dynamics driven by AI-assisted programming, low-code interfaces, and open-space mobile manipulation.**

Robot deployment is not a simple process. Before the process can even begin, manufacturers must identify opportunities where a robot could improve their process. From there, manufacturers must then find the appropriate robot to purchase, and ensure they can get the capital needed to buy it. Both of these steps require a strong understanding of robot capabilities. Once a manufacturer has purchased their robot, they have to integrate it. This can require significant process changes, specialized engineering and software talent, and employee retraining.

### **Intelligent Robots and Flexible Capability Increase Use Cases**

Historically, industrial automation relied on rigid, caged hardware environments designed for high-volume, low-mix (HVLM) production. These setups required specialized system integrators and programmers, lengthy setup times, and significant upfront capital expenditure. This created prohibitive cost barriers and limited product variance, keeping robotics out of reach for low-volume, high-mix (LVHM) manufacturing environments.

#### **Explainer | High-Volume Low-Mix & Low-Volume High-Mix:**

High-Volume Low-Mix (HVLM) refers to manufacturing that produces significant amounts of identical or near-identical products, such as large runs of standardized automotive components. For firms engaged in HVLM manufacturing, production methods and lines can run for years with little to no change. Low-Volume High-Mix (LVHM) manufacturing produces small batches of a greater variety of often highly customized products. LVHM is common in industries, such as defense components, where product needs are highly specified and unique to individual customers.

Modern AI and low-code interfaces have increased flexibility and reduced some programming requirements.<sup>88</sup> These advancements make robotics a more feasible solution, especially for firms engaged in LVHM production, which would need to frequently reprogram robots to adjust to variable products. Agentic AI is also helping build simulation environments, compose software, and test and adapt systems to specific tasks. This can substantially reduce the bespoke engineering required for each deployment and make automation accessible to many more manufacturers.

Concurrently, open-space mobile manipulators, Autonomous Mobile Robots (AMRs), and cobots are being deployed without traditional safety cages or perimeters. These systems are designed to work safely alongside human operators, navigate active factory floors dynamically, and adapt to environmental changes with less human intervention. Those capabilities can ease integration into existing processes and increase flexibility. They are also typically cheaper than large, heavy-duty machines.<sup>89</sup>

For large firms that have already implemented robotics, this can reduce costs and improve efficiency. For SMMs, these developments can shift the cost-benefit analysis in favor of adoption.

## **Safety, Performance, and Liability Frameworks Are Lagging Emerging Robot Capabilities**

As industrial robotics transition from protected cells and fixed routines to open spaces and adaptive responses, legacy safety and performance frameworks are no longer sufficient. Modernizing these standards is essential to ensure operational safety, build worker trust, and enable adoption.

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<sup>88</sup> Roy Sarkar, [How AI is Shaping the Future of Robotics with Low-Code and No-Code Solutions](#), A3 (2026).

<sup>89</sup> Andreas Paleit, [March of the Cobots: the Technology Lowering the Barrier to Automation](#), Financial Times (2025).

### **Explainer | How Standards are Made:**

Standards Development Organizations (SDOs), such as the International Organization for Standardization (ISO), establish standards through specialized working groups consisting of industry, academic, and regulatory experts. Development follows a structured lifecycle including a proposal, draft specifications, and public commentary, before being submitted to an SDO for final approval.

Existing safety standards, such as those developed by ISO and EU SDOs, do not yet fully address every emerging AI-adaptive, multifunctional, or dynamically balancing systems.<sup>90</sup> New robots designed to work around people are typically programmed to move more slowly in proximity to people and freeze if contact is made, which is a partial solution. Additionally, not all form factors have the ability to simply shut off when safety is at risk. For example, dynamically balancing robots, such as bipedal humanoids, require power to remain standing, and an emergency shutdown can create greater danger from a falling robot.<sup>91</sup>

Performance standards are also falling behind. These standards serve as a valuable basis for assessing a robot's capability and reliability, while also allowing comparisons across different robot products. As robots grow more capable and multifunctional, developing standards that can describe the full range of a robot's functionality becomes both increasingly important and difficult.<sup>92</sup>

Robotics companies and industry organizations are currently working to develop new standards, but face challenges addressing rapidly changing capabilities. This lag directly hinders market adoption as manufacturers struggle to evaluate vendors or properly insure robots without trusted frameworks.

New robotic technologies also may require adaptations to insurance and legal frameworks to allow companies to manage risk. Standards and established best practices help courts assess responsibility and insurers price coverage.<sup>93</sup>

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<sup>90</sup> Alexander Robey, et al., [Beyond Alignment: Why Robotic Foundation Models Need Context-Aware Safety](#), Science (2026).

<sup>91</sup> Victoria Turk, [Why Humanoid Robots Need Their Own Safety Rules](#), MIT Technology Review (2025).

<sup>92</sup> Aaron Prather, [Robot Dexterity Has a Benchmarking Problem](#), Six Degrees of Robotics (2026).

<sup>93</sup> [The Robots Are Here: What That Means for Insurers](#), Swiss Re (2017).

## **Service-Based Models Lower Upfront Barriers but Shift Risk to Providers**

Commercial innovations like Robotics-as-a-Service (RaaS) and turnkey subscription models reduce adoption barriers by replacing major hardware purchases with leased systems. Vendors—typically a third-party provider or the robot manufacturer—manage integration, maintenance, and technical support for the robot, while often guaranteeing a baseline level of performance.

This approach reduces risk, upfront capital requirements, specialized staffing requirements, and maintenance costs, and is especially attractive for SMMs, which can struggle to raise the capital for or justify the risks associated with purchasing a sophisticated industrial robot. While this model reduces risk for SMMs, it transfers much of that risk to the service provider itself, which in turn can address those risks through economies of scale that SMMs inherently lack. Still, the economies of scale needed for providers to absorb the risk require high volumes of adoption, leaving the same supply-demand paradox described by Finding 2.<sup>94</sup>

## **Finding 7: Robotics adoption across manufacturing remains constrained by lack of knowledge, internal capability gaps, and unsteady demand signals.**

### **Knowledge, Limited Return Frameworks, and Culture Inhibit Adoption**

A primary obstacle facing non-adopting firms, particularly SMMs, is a lack of knowledge. Many smaller manufacturers remain unsure of what robots can do, where to introduce robotics into their processes, how to select appropriate technologies, or how to navigate integration. Consequently, firms miss opportunities to improve their efficiency.<sup>95</sup>

This gap is compounded by overly narrow return-on-investment (ROI) metrics that measure automation strictly by direct machine output. A complete ROI framework factors in holistic operational gains: smoother throughput, lower process variance, improved worker safety, and the reallocation of staff to higher-value tasks.<sup>96</sup>

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<sup>94</sup> Aditya Ranjan, [Robots in the Enterprise: Why Adoption is Crucial, Yet Lagging](#), Forbes (2024).

<sup>95</sup> [Unlocking the Industrial Potential of Robotics and Automation](#), McKinsey & Company (2023); Briefing to the Commission by an industry expert (July 2026).

<sup>96</sup> Arthur Khare, et al., [Rethinking Digital Transformation Metrics: Moving Beyond Traditional ROI](#), TechRxiv (2024); Briefing to the Commission by an industry expert (June 2026).

Some SMMs also have little incentive to improve efficiency. Firms that are already operating at or above cost often see no need to change when the expected gains do not clearly justify the disruption and investment risk. This is particularly true where owners and senior employees are nearing the end of their careers, since they would benefit from process improvements for a shorter period.<sup>97</sup>

## **Adoption Readiness and Talent are Limited**

Advanced robotics integration requires a baseline of digital infrastructure that small firms may not have. Modern intelligent robots can combine sensor data, 3D design files, digital twins and modeling, and other enterprise data to maximize their utility. If integrating a robot requires a significant digital infrastructure upgrade for a firm, it is more difficult to justify the investment even though the digital infrastructure upgrades might have independent benefits.

Digital infrastructure and robotics integration also come with different talent demands. Even when deployment models such as Robotics-as-a-Service cover the high-level engineering needs, workers require upskilling and new training to work effectively with automated systems.

Regional support networks and programs—including Manufacturing Extension Partnership (MEP) centers, university apprenticeships, collaborative testbeds, and peer demonstration workshops—help overcome some of these barriers, but they are limited in funding, scale, and reach.

### **Example | MEP Centers:**

MEP Centers are the primary federal vehicle for assisting SMMs. They serve as a trusted third-party, neutral consultant for SMMs looking to modernize. Even so, they have limited resources and reach. The program has faced potential cuts from the current administration, which could further limit its impact.<sup>98</sup>

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<sup>97</sup> Briefings to the Commission by industry experts (June 2026, July 2026).

<sup>98</sup> Jeff Kinney, [Trump Again Proposes Eliminating Manufacturing Extension Partnership](#), Manufacturing Dive (2026).

## New Digital Systems Bring New Cybersecurity Risks

New digital infrastructure brings new cybersecurity risks. Manufacturing is one of the most targeted industries, and, because operational downtime is uniquely expensive, attacks on manufacturing are generally more costly than those on other sectors.<sup>99</sup>

Most of these attacks are ransomware, designed to extort money in exchange for restoring operation or data, but as the role of digital systems in manufacturing increases, attack vulnerability expands.<sup>100</sup> In particular, exploits that seize control of physical manipulators would enable attackers to cause physical damage and prolonged disruption. At the same time, frontier AI models are demonstrating increasingly powerful cyber capabilities, which could increase attackers' capabilities while also improving defensive tools.<sup>101</sup>

The cybersecurity risk is particularly pressing for manufacturers in critical sectors, as they may be targeted by adversaries. Such attacks are currently occurring, as Iran and Iranian-affiliated actors engage in broad cyberattacks to disrupt the operation of American critical infrastructure as part of ongoing hostilities,<sup>102</sup> and in 2025, a number of U.S. Government entities including the Federal Bureau of Investigation and the National Security Agency published a joint memo indicating that such companies are at increased risk of attack.<sup>103</sup>

The risk is even more acute for technologies manufactured by adversarial nations, which may contain backdoors. This is underscored by the FCC Covered List determination discussed in the National Framework section, which restricts new equipment authorizations for qualifying foreign-produced advanced robotic devices, subject to applicable exceptions, without categorically distinguishing allied from adversary production.<sup>104</sup>

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<sup>99</sup> C. David Hylender, et al., [2026 Data Breach Investigations Report](#), Verizon at 88-89 (2026); C. David Hylender, et al., [2026 Breach Impact Study](#), Verizon at 26 (2026).

<sup>100</sup> Aaron Prather, [The End of Dumb Robots](#), Six Degrees of Robotics (2026).

<sup>101</sup> Robert McMillan & Chip Cutter, [AI Is Finding Bugs That Hackers Can Exploit. Get Ready for Bugmageddon](#), Wall Street Journal (2026).

<sup>102</sup> [Iranian-Affiliated Cyber Actors Exploit Programmable Logic Controllers Across US Critical Infrastructure](#), CISA (2026).

<sup>103</sup> [Iranian Cyber Actors May Target Vulnerable US Networks and Entities of Interest](#), CISA (2025).

<sup>104</sup> [FCC Adds Foreign-Produced Power Inverters and Robots to Covered List](#), FCC (2026).

## Long-Term Demand Stability is Necessary for Automation Investment

Unsteady and fragmented demand signals severely disincentivize automation. Implementing robotics requires significant investment in capital, process improvement, and workforce development. Firms cannot justify that when order volumes are volatile or uncertain. More predictable demand and long-term contracts can help justify the financial risk or fixed cell architectures required for automated equipment.

This dynamic reflects the supply-demand paradox described in Finding 2. Demand can stimulate supply and expand capacity, but increasing the supply of robots alone will not make manufacturers ready to buy them. The same constraint applies to the products those robots help produce.

## How Four Adoption Barriers Reinforce One Another

Widespread industrial robotics adoption is constrained by four primary structural hurdles. **Financial** barriers in the form of significant upfront capital expenditures for hardware and integration are difficult to justify. Even with help from models like RaaS, justifying the cost requires secure expectations of demand for a product.<sup>105</sup>

**Readiness** requires modern digital infrastructure and human talent to integrate, operate, and maintain robots for short- and long-term use, posing additional hurdles to first-time adopters.

**Risks and liability** require robust safety standards and cybersecurity practices that clarify responsibility, support affordable insurance coverage, and provide legal certainty after an accident.

Finally, a pervasive **knowledge gap** leaves many firms unable to identify automation opportunities or evaluate evolving capabilities. While external support networks help bridge this gap, they are limited in scope and capability. Compounding these challenges, many established firms, particularly those with owners and workforces nearing retirement, may see insufficient near-term returns to justify disruption and investment.

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<sup>105</sup> Briefing to the Commission by an industry expert (June 2026).

# Innovation Ecosystem: Supply-Chain, Financing, Data, and Cost Constraints Prevent U.S. Robotics Firms from Scaling

If adoption is the demand side of the flywheel, the innovation ecosystem is the supply side. America's robotics strength is concentrated in the "brain," but software strength alone cannot produce or deploy physical systems at scale (the "body"). Explaining why U.S. leadership in AI and software is insufficient requires addressing the physical constraints of deployment and integration for robotics companies and SMMs alike. Hardware cannot be scaled through digital iteration alone; physical systems must overcome severe technical, supply-chain, financing, data, and cost constraints to operate reliably in industrial environments. It is also critical to have real-world deployments to test and validate innovative AI-powered systems—meaning that access to hardware and development of the state-of-the-art brain go hand-in-hand. Sustaining leadership in physical AI therefore requires access to hardware and production environments where systems can be tested and improved.

Next-generation physical systems require robust perception in unstructured settings, precise tactile sensing, dexterous manipulation, safe human-robot collaboration, high-performance onboard compute and connectivity, long-term reliability, maintainability, and fast reprogramming for high-mix production environments. Compute platforms like NVIDIA's Jetson Thor supply high computational throughput, yet processing power cannot compensate for deficiencies in underlying physical components such as actuators, sensors, and structural interfaces.<sup>106</sup>

Physical products also face different commercialization economics than software. Software benefits from near-zero marginal distribution costs, rapid deployment, and high operational tolerance for iterative software patches. Conversely, physical hardware demands extended development cycles, rigorous safety and operational certifications, substantial upfront manufacturing tooling, working capital for inventory, long-term warranty liability, complex field service operations, and an extremely low tolerance for catastrophic physical failure.<sup>107</sup>

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<sup>106</sup> [NVIDIA Announces Jetson Thor, Powered by an NVIDIA Blackwell GPU](#), Humanoid Robots Technology (2025).

<sup>107</sup> Mike Palank, [The State of Technology & Culture: A Return to Hard Tech](#), Mac Venture Capital (2026).

To structure the analysis of physical commercialization economics, particularly among small and medium manufacturers, this section examines four constraints identified in Findings 8 and 9: opaque and concentrated supply chains; financing and integration gaps; scarce data for adaptable robots; and the cost pressures created by scale and state-supported market behavior.

## **Finding 8: Systematic cost disadvantages and a financing gap keep U.S. robotics firms from scaling production.**

### **Opaque and Concentrated Supply Chains Create Strategic Bottlenecks**

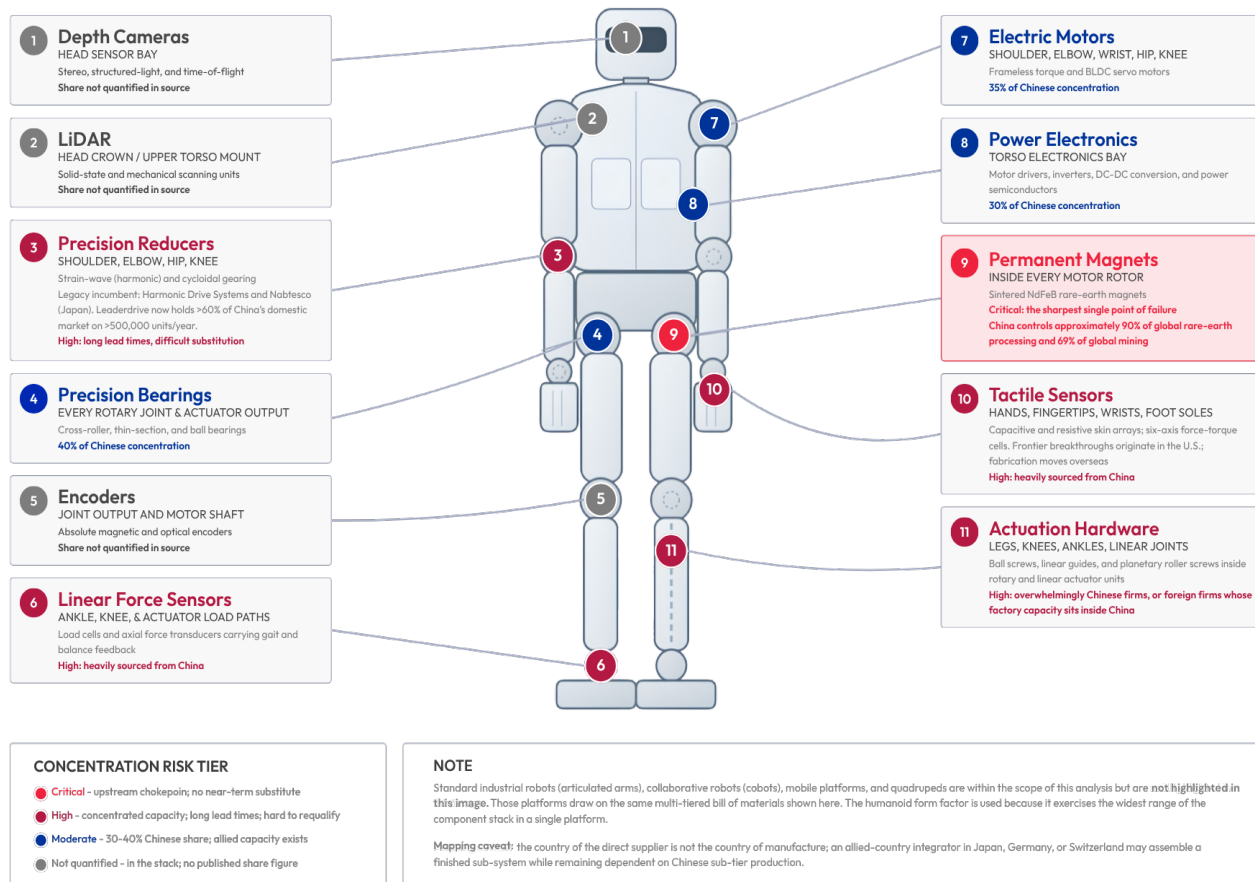
Most robotic systems draw on a globally distributed component stack: magnets, motors, precision reducers, actuators, bearings, encoders, force and tactile sensors, depth cameras, LiDAR, and power electronics. Dependence becomes strategic when concentrated suppliers, opaque sub-tiers, or adversary-linked production can disrupt scale, expose sensitive systems, or set market terms, as the FCC's recent actions, in response to a national security determination, against foreign-produced connected equipment, underscored.<sup>108</sup> Standard industrial robots, mobile platforms, quadrupeds, and humanoids rely on a multi-tiered bill of materials.

#### **Figure 15 | Humanoid Component Stack: Where the Bill of Materials Sits**

*Takeaway: Callouts locate each subsystem on the platform. Color indicates the degree of concentration risk in Chinese production capacity.*

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<sup>108</sup> National Security Determination on the Threat Posed by Foreign-Produced Advanced Robotic Devices, Federal Communications Commission (2026).



Source: McKinsey & Company<sup>109</sup>

A primary risk in supply chain mapping is mistaking the location of a direct supplier for the origin of the underlying components.<sup>110</sup> An allied-country integrator in Japan, Germany, or Switzerland may assemble finished subsystems while remaining dependent on Chinese sub-tier manufacturing. For example, in the actuation stack, components such as ball screws, linear guides, and planetary roller screws are overwhelmingly manufactured by Chinese firms or foreign companies whose primary factory capacity sits within China.<sup>111</sup> Historically, the global market for high-precision strain wave reducers was heavily consolidated under Japanese legacy manufacturers like Harmonic Drive Systems and Nabtesco, but now companies like Leaderdrive hold over 60% of the

<sup>109</sup> [Turning humanoid supply chain constraints into billion-dollar wins](#), McKinsey & Company (last accessed 2026).

<sup>110</sup> [The Robotics Supply Chain: Components, Suppliers and Dependencies](#), Yana Sourcing (last accessed 2026).

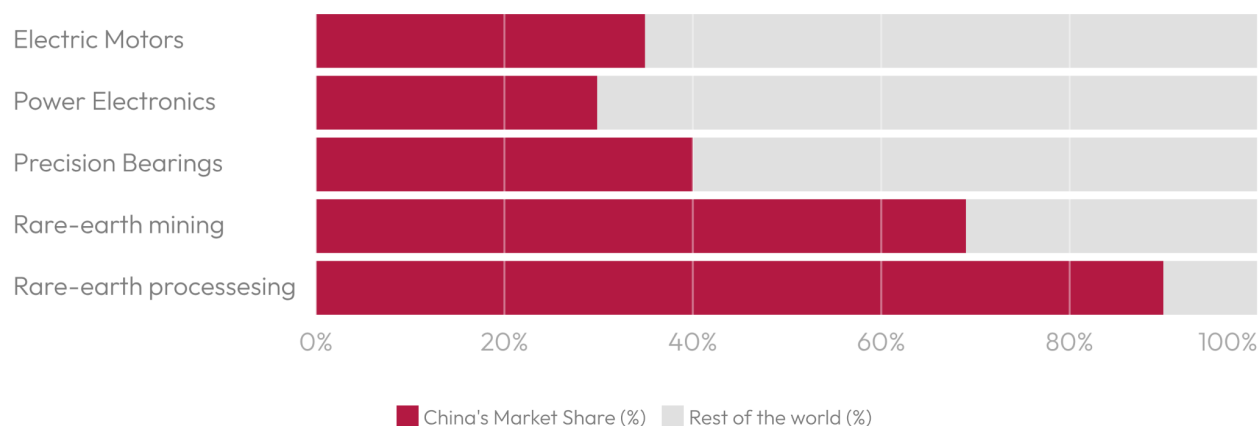
<sup>111</sup> Rob D. Atkinson, et al., [A Time to Act: Policies to Strengthen the US Robotics Industry](#), Information Technology & Innovation Foundation (2025).

Chinese domestic harmonic reducer market on annual production capacity exceeding 500,000 units.<sup>112</sup>

While consolidating manufacturing through these Chinese suppliers is highly cost-effective, it creates severe supply-chain bottlenecks.<sup>113</sup> High-risk bottlenecks exist where production is concentrated, lead times are long, or substitution is technically difficult.<sup>114</sup> Linear force sensors and tactile sensors are heavily sourced from China; even when frontier breakthroughs in tactile sensing originate in the United States, actual physical manufacturing predominantly moves overseas. Permanent magnets are the sharpest single point of failure: China controls approximately 90% of global rare-earth processing capacity and 69% of global rare-earth mining. Chinese concentration in humanoid components is pronounced: precision bearings at 40%, electric motors at 35%, and power electronics at 30%.<sup>115</sup>

### Figure 16 | China's Market Share in Humanoid Robotics Inputs and Components

*Takeaway: China controls a majority of the rare-earth processing capacity as well as the global rare-earth mining capacity. The result is that a single supplier nation sets the availability and price of an input for which there is no near-term substitute.*



Source: International Energy Agency<sup>116</sup>

<sup>112</sup> [Company Introduction](#), Leaderdrive (last accessed 2026).

<sup>113</sup> [China's Robotics Supply Chain in 2026: Cost Advantage, Localization and Global Market Power](#), Robots Daily (2026).

<sup>114</sup> [Behind every robot: why component supply chains are the real bottleneck in robotics scale-up](#), Market Scale (2026).

<sup>115</sup> [Rare Earth Elements](#), International Energy Agency (2026).

<sup>116</sup> [Rare Earth Elements](#), International Energy Agency (2026).

The United States' structural disadvantage in scaling robotics production lies less in any single input than in its ecosystem: a weakened machine-tool base and a thin network of upstream suppliers that, in China, are sustained by demand from many industries at once. In 2022, China produced \$27.1 billion in machine tools—approximately 4.6 times U.S. output of \$5.9 billion. This gap reflects a long erosion of domestic capacity: after accounting for roughly one-fifth of the global machine-tool market at the beginning of the 1980s, the U.S. industry lost more than two-thirds of its firms in the contraction that followed.<sup>117</sup> The more consequential effect is often slower iteration rather than longer production lead times. Shenzhen's dense supply network provides same- or next-day access to components and 24-hour circuit-board turnaround, allowing hardware companies to complete prototype iterations in as little as 24 to 48 hours.<sup>118</sup> This density is not a product of robotics demand. The motors, sensors, batteries, and power electronics that robotics firms source in China are produced at scale for consumer electronics, electric vehicles (EVs), drones, and appliances, and robotics benefits from volumes it could not generate on its own. This compresses the design-to-part feedback loop and enables Chinese firms to test, modify, and improve products faster than competitors operating in less concentrated manufacturing ecosystems. Rebuilding comparable upstream capacity in the United States would therefore depend on demand from adjacent industries, not robotics alone.

Retooling for extreme tolerances compounds the delay. Onboarding a new manufacturer for a production-ready electronics product can take 12 to 20 weeks to first-article approval, and Production Part Approval Process (PPAP) documentation, requalification, and new tooling builds push stable volume production four to six months out.<sup>119</sup> Changes that affect tooling can require renewed qualification, while Section 232 tariffs and the 2026 tungsten price surge raise the cost of retooling—a direct burden on robotics, whose frames, housings, motors, reducers, and wiring are metal-intensive and whose high-tolerance gears, shafts, and bearing surfaces are machined with tungsten-carbide cutting tools.<sup>120</sup> Tariffs can encourage substitution toward domestic suppliers

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<sup>117</sup> Trelysa Long, [Mapping Industrial Strength: U.S. Machine Tool Production and Consumption](#), Information Technology and Innovation Foundation (2025); David Finegold, et al., [The Decline of the U.S. Machine-Tool Industry and Prospects for Its Sustainable Recovery](#), RAND (1994).

<sup>118</sup> James Kynge, [Transcript: China Tech—Shenzhen Speed](#), Financial Times (2024).

<sup>119</sup> [Scaling to Production Without Switching Your Manufacturer](#), Amtech (last accessed 2026).

<sup>120</sup> David Willson & Steve Melito, [PPAP: Production Part Approval Process Guide for Manufacturing](#), Fictiv (2025); [Machining Trends in 2026: Automation, Workforce Challenges, and Reshoring](#), Kent USA (2026); [Further Adjusting the Tariff Regimes For Imports of Aluminum, Steel, and Copper into the United States](#), The White House (2026); Camilla Hodgson & Sylvia Pfiefer, [Iran War Sparks Upheaval in Niche Defence](#)

over time, but by raising the cost of the very tooling and metals that move requires, they make rapid switching economically difficult in the short term.

That switching problem feeds into an additional barrier. Long supplier-change timelines can reinforce manufacturers' reliance on established intermediaries, reducing the incentive to identify and qualify the original producer. This opacity reflects a broader supply-chain problem: in a 2026 survey of 2,805 organizations across construction, energy, manufacturing, transport, the public sector, and other industries, only 6.2% reported full visibility into their Tier 2 and Tier 3 suppliers.<sup>121</sup> That blindness carries real security and reliability costs. The Unitree findings described in the National Framework section illustrate the consequence: its robots stream camera, microphone, and location data to servers in China, and every unit reportedly shipped with the same built-in encryption key, allowing one compromised key to expose every unit.<sup>122</sup> The U.S. Cybersecurity and Infrastructure Security Agency (CISA) has also warned this year that a flaw in Universal Robots' control software allows anyone on the network to take over a factory robot's controller without a password.<sup>123</sup> The United States cannot secure or scale a supply chain it cannot see.

## **Hardware Timelines and Customer Risk Aversion Create a Commercialization Valley of Death**

Robotics startups may attract strong early interest, but industrial hardware requires patient capital for certification, manufacturing, inventory, field deployment, and service before recurring scale is visible. Hardware commercialization progresses through distinct development phases: basic research, prototyping, pilot demonstrations, system productization, safety/regulatory certification, manufacturing tooling, inventory build-out, channel distribution, and recurring field service. Capital fit must match the distinct requirements of each stage.

Measured against that requirement, the dominant source of early-stage capital is poorly matched. Traditional venture capital models are structured around software economics—favoring high gross margins, rapid iterative scaling, asset-light footprints,

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[Metals Market](#), Financial Times (2026); [Tungsten Statistics and Information](#), U.S. Geological Survey (last accessed 2026); [Gear Milling](#), Sandvik Coromant (last accessed 2026).

<sup>121</sup> [The Achilles Annual Risk and Sustainability Report 2026](#), Achilles Global Risk Management (2026).

<sup>122</sup> Sinisa Markovic, [Humanoid robot found vulnerable to Bluetooth hack, data leaks to China](#), Help Net Security (2025).

<sup>123</sup> [CVE-2026-8153: Command Injection in the PolyScope 5 Dashboard Server](#), Universal Robots (last accessed 2026).

and minimal capital expenditure. The mismatch is structural, not merely stylistic: a ten-year fund life with distribution pressure beginning mid-term cannot easily accommodate a product that reaches serial production in year seven. Hardware startups require upfront physical tooling, long-term testing, hardware safety compliance, and physical maintenance networks, leaving them chronically undercapitalized during the transition from pilot to serial manufacturing.

The demand side offers no offsetting relief. Industrial customers frequently engage in paid pilot programs or technical demonstrations to evaluate new robotic technologies. However, customers rarely commit to multi-year, large-volume purchase contracts without proven field reliability. This creates a deadlock: startups cannot secure financing to scale manufacturing without binding orders, and buyers will not issue binding orders without proof of scalable manufacturing capability.

Breaking this deadlock depends less on the aggregate volume of capital than on its structure. Capital availability must be evaluated by instrument type and product alignment. Venture equity is suited for early-stage software and architectural design; working capital debt, equipment financing, project finance, strategic corporate co-investment, and non-dilutive government funding and procurement grants are required to build precision manufacturing lines and manage physical inventory liability. Aggregate venture funding figures obscure hardware deficits when software-heavy platforms absorb the majority of private investment.

Capital is less likely to flow when the operational evidence needed to prove performance and adaptability remains scarce. Fortunately, physical AI is seeing increasing interest from venture capital, with both deal number and deal volume nearly doubling from Q1 2024 to Q1 2026.<sup>124</sup> Commission analysis found, however, that a significant portion of that funding was focused on humanoid robotics, which accounted for more than 20% of the funding while representing only 3% of the firms.

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<sup>124</sup> Ali Javaheri, [Robotics & Physical AI VC Trends](#), PitchBook (2026).

## **Finding 9: Supply chain bottlenecks for physical components and data keep U.S. robotics too expensive and too static.**

### **Limited Deployment and Proprietary Systems Keep Robotics Data Scarce and Fragmented**

Robotic systems get better by working. Each deployment generates data, the data improves performance, and better performance justifies the next deployment. This flywheel is barely turning in the United States. The United States lacks robotics data: the data U.S. firms produce sits locked inside individual firms, in incompatible formats and behind contracts that bar sharing, so no one can pool and learn from it. This means it never adds up to a shared national asset.

Training robotics takes far more kinds of data than training a chatbot, which learns from text and images. The data modalities (i.e. the types of data) required to train robots are far broader and not as easy to aggregate. A robot needs a record of a human operator guiding it through a task (known as teleoperation) to show what the person meant to do. It needs touch, force, and depth readings to learn what happens when it makes contact with an object. Machine logs show how parts wear and where systems fail over time. Process context explains why a task is performed a certain way, and whether each attempt worked. A model trained on visual data alone can learn to move a box. It cannot learn the fine control of force that a robot needs to assemble a wire harness.

Real-world robotics data often costs more to collect than widely available web data because it requires physical demonstrations, equipment, and task-specific measurement.<sup>125</sup> Open X-Embodiment, the largest open real-robot dataset, pooled 60 datasets from 34 laboratories. It covers 22 types of robots and 527 skills. It resulted in a total of about one million recorded robot trajectories which each took a physical robot to produce.

Simulation and synthetic data can reduce some of these collection costs. This synthetic data collection process enables developers to generate training examples, test policies, and explore operating conditions in virtual environments. This works best for perception and movement, where the physics are simpler and a virtual scene is easy to

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<sup>125</sup> Alexander Khazatsky, et al., [DROID: A Large-Scale In-The-Wild Robot Manipulation Dataset](#), DROID dataset (2025).

manipulate.<sup>126</sup> For industrial customers, this work could be less effective as assembly requires precise contact, flexible materials such as wire harnesses, the sense of touch and force, and is vulnerable to equipment wear and tears over time. For these tasks, a simulation is only useful if it matches real equipment, materials and friction, and the only way to check that match is against measurements from real machines.<sup>127</sup> Simulated data therefore extends real data rather than replacing it. A small set of high-quality real demonstrations can anchor a much larger set of virtual ones, but a simulation with no-real world grounding repeats its own mistakes at scale. Physical testing remains necessary to validate performance and safety under actual operating conditions.

Even with simulation, the data gap is structural rather than incidental. Physical data cannot be scraped; capturing it requires active execution that consumes hardware life, demands purpose-built environments, and degrades expensive equipment. The resulting streams are also enormous and largely unstandardized. A typical robot cell is supplied end-to-end by one vendor with proprietary and mutually incompatible programming and diagnostic libraries, promoting lock-in and preventing operational data from being pooled.<sup>128</sup>

Even the data the United States generates rarely reaches the models that could learn from it, and firms in China withhold data for the same commercial reasons U.S. firms do. Beijing's response has been not to argue firms out of that calculus, but to pay to circumvent it through state-financed training centers, mandated scenario access at central state-owned enterprises, and subsidies for datasets released openly.<sup>129</sup> Encryption does not solve this: factories and other robot users are not worried about hackers reading their data, but about giving their robot supplier a view into how they operate, especially when that supplier also sells to their competitors.<sup>130</sup>

Operational data reveals process know-how that firms treat as trade secrets. Its transfer creates intellectual property and contractual exposure across the production, integrator, and end-user chain. Telemetry pipelines expand cyberattack surface into operational technology networks, and any downstream physical incident raises

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<sup>126</sup> Josh Tobin, et al., Domain Randomization for Transferring Deep Neural Networks from Simulation to the Real World (2017).

<sup>127</sup> Zhibin Li, et al., Closing the Reality Gap: Zero-Shot Sim-to-Real Deployment for Dexterous Force-Based Grasping and Manipulation, ByteDance Seed (2025).

<sup>128</sup> Michael Browne, [A Uniform Interface for Robots](#), Automation World (2021).

<sup>129</sup> Phillip An, [ISF Voices 2026: The Robotics Data Gap: How Training Data Pipelines Will Shape the Global AI Race](#), Special Competitive Studies Project (2026).

<sup>130</sup> Kevin Riedl, [Fully Homomorphic Encryption in 2026: What Ships and What Is Still Hype](#), Wavect (2026).

unresolved questions about whose data trained the failing system. Non-interoperable proprietary schemas make sharing technically costly even where the parties are willing. Industrial data is abundant in aggregate and inaccessible in practice.<sup>131</sup> Data and learning can improve performance, but systems must also reach price and total-cost levels that make broad deployment feasible.

**Scale, Supplier Density, and State Support Give Chinese Producers a Structural Cost Advantage**

Chinese robots and components are cheaper than Western equivalents because of manufacturing scale, supplier density, learning effects, lower production costs, and state-supported market behavior. A U.S. response must separate the structural drivers from the policy-contingent ones. Scale and supplier density are durable: China installed 295,000 industrial robots in 2024, 54% of global deployments, and domestic firms took 57% of their home market, up from roughly 28% a decade ago.<sup>132</sup>

The U.S. cost disadvantage is not primarily a function of labor rates. It rests on component supplier density, infrastructure readiness, capital availability, system utilization rates, tax and regulatory environments, and the scale of predictable end-market demand.

**Figure 17 | Total cost of ownership encompasses a much broader financial commitment**

| Cost Category            | Key Components                                                                        |
|--------------------------|---------------------------------------------------------------------------------------|
| Initial Procurement      | Motors, sensors, reducers, and power electronics.                                     |
| System Integration       | Custom software integration, cell engineering, and safety validation.                 |
| Operations & Maintenance | Preventive maintenance, tooling, scheduled downtime, and operator training.           |
| Lifecycle Support        | Financing interest, warranty claims, field service coverage, and security compliance. |

Source: SCSP Analysis

<sup>131</sup> Ryan Fletcher, et al., [Tapping into dormant data can boost industrial SMEs’ competitive edge](#), McKinsey (2023).

<sup>132</sup> [China Tops World Record of 2 Million Factory Robots](#), International Federation of Robotics (2025).

The hardware purchase price also understates what a deployment costs. A robot arm enters service inside an engineered cell, and the cell carries costs the arm does not: custom software integration, safety validation, tooling and fixturing, enclosure, operator training, preventive maintenance, warranty and field service, financing interest, and security compliance. One FANUC-certified integrator puts the robot itself at roughly a quarter of a total cell cost.<sup>133</sup>

Unit costs fall along predictable learning curves driven by production volume and supplier cluster density. China leverages dense manufacturing ecosystems, enabling rapid iteration and low component pricing across actuators, precision gearboxes, and power electronics. Conversely, integration costs in the United States remain high because deployment is fragmented, engineering is one-off, and digital readiness in mid-tier manufacturing facilities is low.

Foreign competitors do not just benefit from organic supply-chain depth. They are buoyed by aggressive supply-side state subsidies, public capital infusions, and highly clustered supplier networks, plus a culture driven by government and social attitudes that welcome automation and industrial innovation. Among publicly listed Chinese robotics firms, government subsidies have accounted for as much as 40% of net profit in some years.<sup>134</sup> These once funded low-utility, high-volume producers; today, Chinese suppliers deliver high-performing, globally competitive systems. While the United States and its allies retain a decisive edge in system longevity, software integration, high-end compute, firmware security, and specialized application fit, they face intense price compression in standardized hardware categories.

Replicating China's low-cost legacy component supply chain is not the answer; bypassing the chokepoint is. China manufactures 94% of the world's permanent magnets, and U.S. startups are engineering non-rare-earth motor alternatives in response. Industrial robots are bought in known duty cycles and serviced on predictable schedules, which makes them a comparatively low-risk proving ground for alternative magnet chemistries: performance can be observed across a defined service life before the technology is committed to less forgiving applications.<sup>135</sup> Ultimately, supply-chain depth, suitable capital, usable data, and production volume collectively determine both

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<sup>133</sup> [What is the Range of Robot Cost?](#), Motion Controls Robotics (last accessed 2024).

<sup>134</sup> Hong Cheng, et al., [Rise of the Robots in China](#), Stanford's Centers on China's Economy and Institutions (2021).

<sup>135</sup> [Rare Earth Elements](#), International Energy Agency (2026).

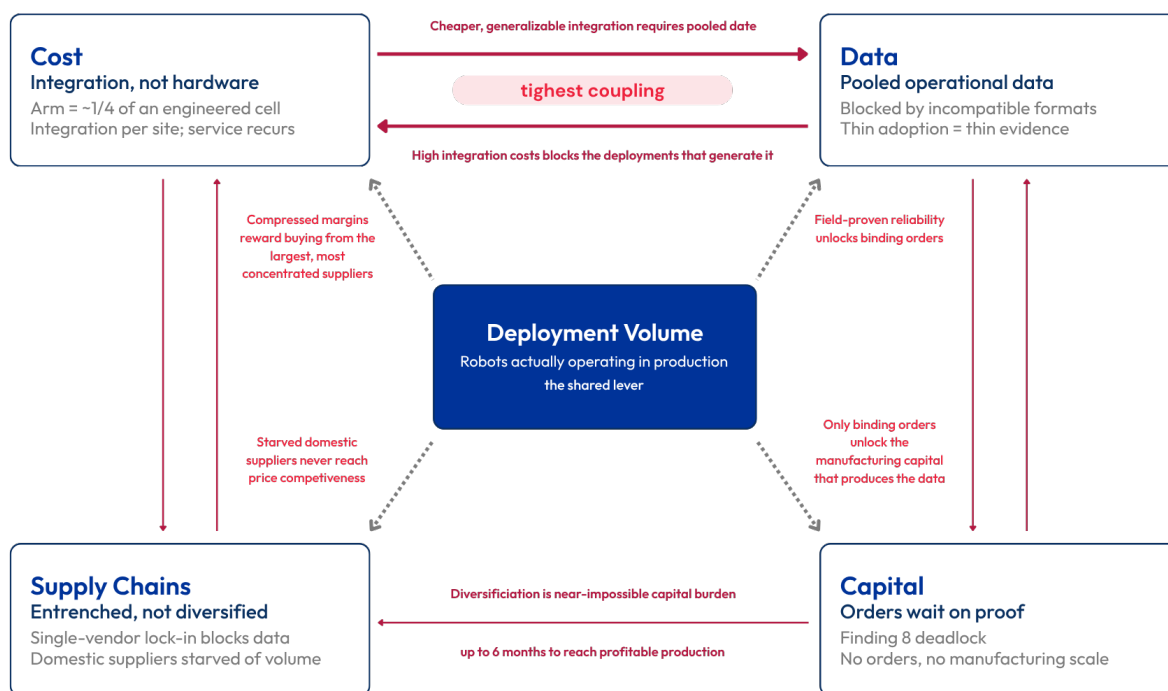
cost and capability. None of these elements can be solved in isolation; the U.S. strategy must address them as a unified ecosystem.

## Low Deployment Links Supply-Chain, Capital, Data, and Cost Constraints

Supply chains, capital, data, and cost are not four independent problems. They are one system where each supplies the conditions that sustain the others. Any national strategy must account for how these constraints interact.

Figure 18 | Ecosystem Interactions

*Takeaway: Each constraint supplies the conditions that sustain the others.*



\*Solid arrows = reinforcing constraints, thicker where coupling is tightest. Dashed = the lever that relieves all four at once.

### China is running the same loops forward while they run backwards in the U.S.

Installed base roughly 5x America's; domestic firms control 57% of their home market. Any effective intervention must target deployment volume directly – funding that puts no robots in production fails.

Source: SCSP Analysis

The tightest coupling runs between data and cost. Integration, not hardware, drives the cost of a deployment: the arm is roughly a quarter of an engineered cell, integration is incurred per site, and service and uptime recur across the asset's life whereas a

purchase discount is realized only once.<sup>136</sup> Integration is expensive because every cell is engineered once, for one process, on one vendor's proprietary stack. Generalizable integration is therefore a data problem: it requires precisely the pooled operational data that incompatible formats and low adoption rates prevent the market from producing. AI could also make integration cheaper by letting robots learn new tasks from examples rather than being programmed by hand for each process, but those models are only as good as the operational data they are trained on. Simulation can ease some of this burden, because integrators can design and test a robot cell on a computer before building it. But a virtual model of a cell is only as accurate as the real-world data used to build and check it. Simulation therefore raises the value of deployment data rather than removing the need for it. This creates a vicious cycle (as shown above): high integration cost prevents new deployment, which starves the system of the data needed to make integration cheaper.

Cost pressures also force firms to entrench their existing supply chains rather than diversify them. Because margins on standardized hardware are so compressed, firms are rewarded for buying from the largest, most concentrated suppliers. Transitioning to new suppliers is slow and expensive, requiring up to six months to reach profitable production, thus making diversification a nearly impossible capital burden for under-resourced firms. This deepens market dependency where single-vendor systems impede the data interoperability needed to reduce overall integration costs, while domestic hardware suppliers are starved out of the order volume required to become price competitive. Ultimately, the current market structure financially punishes firms for making strategically resilient decisions.

Capital and data close the remaining loop as the deadlock described in Finding 8: binding orders wait on field-proven reliability, and reliability data waits on the manufacturing capital that only binding orders unlock. Every actor makes the financially rational choice, and the system stalls anyway.

The volume of robots operating in production is the central metric connecting these structural challenges. High deployment acts as a multiplier: it drives down costs, generates capability-enhancing data, proves the field reliability needed to unlock demand, and creates the order volume required to sustain a domestic supply chain. Currently, China is exploiting this exact feedback loop to its advantage. China has built an installed base of industrial robots roughly five times larger than America's, with

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<sup>136</sup> [What is the Range of Robot Cost?](#), Motion Controls Robotics (last accessed 2026).

domestic firms controlling 57% of their home market. The systemic loops compounding U.S. stagnation are the exact ones accelerating Chinese dominance. Any effective policy intervention must directly target deployment volume to solve all four constraints at once. Initiatives that do not put physical robots into productive use, regardless of how heavily they are funded, will not address the central constraint.

# Looking Forward: Converting U.S. Robotics Innovation into Industrial Scale

## **Finding 10: A national mission is needed to start the U.S. robotics flywheel.**

The findings in this report point to a common conclusion. The United States does not lack robotics research, entrepreneurial activity, capable manufacturers, or public programs. It lacks a mechanism for converting those strengths into deployment and production at sufficient scale. Manufacturers hesitate because robotic systems remain costly, difficult to integrate, and insufficiently proven for many applications. Suppliers and integrators hesitate to invest because demand is fragmented. Workers and training providers face uncertain signals about future skill needs, while capital waits for evidence that only wider deployment can generate. Each actor's decision can be rational in isolation while the system as a whole remains stalled.

Breaking that equilibrium requires a national strategy organized around deployment. The number of robots operating productively in American factories is not the only measure of progress, but deployment is the variable that connects the others. It generates operating data and integration experience, creates demand for hardware, components, and services, and gives manufacturers and workers greater confidence in the technology. At sufficient scale, those effects can improve performance, reduce costs, strengthen suppliers, and encourage further adoption. Deployment is therefore not simply the final step in commercialization. It is part of the process through which the technology, production base, and workforce improve.

Deployment alone, however, is not sufficient. If the United States expands adoption while remaining dependent on insecure supply chains or adversary-linked components, proprietary systems that cannot interoperate, insecure networks, or a workforce pipeline too thin to operate and maintain them, greater use could deepen rather than reduce national vulnerability. The objective must be responsible and economically sustainable deployment that also strengthens domestic and allied production capacity, cybersecurity, supply-chain resilience, and opportunity for American workers.

A national strategy should emphasize significant onshoring of robotics hardware production but not require domestic production of every component, nor should the government select a single technological architecture. The United States should not

attempt to reproduce China's state-directed industrial model. The American approach should mobilize the country's own comparative strengths: private-sector competition, world-leading research, deep capital markets, regional manufacturing ecosystems, skilled workers, and close relationships with allies and partners. The government's role is to establish clear national objectives, address coordination failures, reduce barriers that individual firms cannot overcome alone, and create the conditions in which private investment and competition can operate at greater speed and scale.

The four pillars identified in this report describe the mutually reinforcing elements of that effort. A national strategy can align fragmented federal activity, clarify standards and security expectations, and build public trust. A stronger talent pipeline can ensure that manufacturers have the technicians, engineers, integrators, and researchers they need while preparing workers to benefit from technological change. Wider adoption—particularly among small and medium-sized manufacturers—can create the demand and operational learning needed to support a larger domestic market. A more capable innovation ecosystem can turn American research into commercial products, address critical component and financing gaps, and help firms move more reliably from prototype to volume production. Progress on any one pillar will be limited without progress on the others.

Such a mission should be judged by national outcomes rather than by the number of programs created or dollars announced. Relevant measures include the breadth of robotics adoption across industries, regions, and smaller manufacturers; the time and cost required to move from assessment to productive operation; the share of pilots that advance to repeat deployments; domestic and allied capacity in critical components; the availability of integration and maintenance services; workforce entry and advancement; and the security and interoperability of deployed systems. These measures would make it possible to identify bottlenecks, assess whether interventions are working, and adjust course as technology and markets evolve.

This Preliminary Report provides a diagnosis rather than a complete prescription. In its next phase, the Commission will evaluate the choices and tradeoffs within each pillar and develop recommendations for federal, state, and regional leaders; manufacturers and technology companies; educators and workforce-development organizations; workers and labor representatives; investors; and research institutions. The Final Report will identify where national coordination is indispensable, where government can best enable private action, and which strategic targets can produce measurable progress.

The United States retains substantial advantages, but the opportunity to convert them into durable industrial leadership will not remain open indefinitely. No single technological breakthrough, subsidy, or institution can create the necessary scale on its own. A sustained national strategy can begin the self-reinforcing cycle of adoption, production, learning, and innovation—and help ensure that the United States leads not only in the intelligence that powers the machines of the future, but also in the capacity to build, deploy, secure, and sustain them.

# Appendix & Supplemental Content

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# Glossary of Terms

**Actuator:** The robotic component that produces a robot's motion.

**Attack Surface:** The full set of ways a cyber attacker could get into a system.

**Autonomous Mobile Robot (AMR):** A robot that drives itself around a facility, autonomously navigating rather than following a fixed track.

**Ball Screw / Linear Guide:** Precision mechanical parts that convert a motor's spin into straight-line motion. Used throughout robot arms and machine tools.

**Bill of Materials (BOM):** The complete parts list for a product.

**CNC Machine (Computer Numerical Control):** A cutting or shaping machine driven by a computer program.

**Collaborative Robot (Cobot):** A robot designed to work safely alongside people without a protective cage.

**Digital Twin:** A detailed virtual model of a machine, work cell, or entire factory that mirrors the real one.

**Duty Cycle:** The pattern of how much a machine runs versus rests over a given period.

**Firmware:** Specialized software permanently embedded into a hardware device to provide low-level control and operating instructions.

**First-Article Approval / Production Part Approval Process (PPAP):** The formal qualification a new supplier must pass before volume production begins.

**Fixturing:** The clamps, jigs, and holders that position a part for a robot or machine to work on.

**Form Factor:** The primary physical form of a robot, e.g. humanoid, quadruped, arm.

**High-Volume Low-Mix (HVLM):** Manufacturing of a large amount of very similar or near-identical products, e.g. car manufacturers.

**Humanoid Robot:** A robot roughly resembling a human shape, typically with a head, a torso, two arms, and two legs.

**Industrial Robot:** A programmable machine used to perform physical tasks in an industrial setting.

**Industry 4.0:** The current phase of industrial development that integrates advanced digital technologies, automation, and real-time data into manufacturing and industrial processes.

**Installed Base / Operational Stock:** The total number of robots in service in a country.

**Interoperability:** The ability of equipment and software from different vendors to work together and exchange data.

**LiDAR:** A sensor that builds a 3D map of its surroundings.

**Low-Code Interface:** A sensor that builds a 3D map of its surroundings.

**Low-Volume High-Mix (LVHM):** Manufacturing of a variety of different products in small amounts, e.g. defense system components.

**Manufacturing Extension Partnership (MEP):** A nationwide network of 51 centers, funded through the National Institute of Standards and Technology and non-federal partners, with at least one in every state, that gives small and medium manufacturers hands-on, vendor-neutral technical advice on modernization, including automation.

**Manufacturing USA:** A network of 18 federally sponsored public-private institutes, each focused on a specific advanced manufacturing technology, that connect industry, universities, and government through shared research, pilot facilities, and workforce training.

**Mechatronics:** The combined discipline of mechanical, electrical, and software engineering required to build and maintain automated systems.

**Mobile Manipulator:** A robot that pairs a moving base with one or more arms, allowing it to autonomously navigate and physically handle objects.

**Operational Technology (OT):** The computers and networks that directly control physical equipment on a factory floor.

**Permanent Magnet:** A magnet that holds its magnetic field without any electricity, essential to the compact, efficient motors inside robots. The highest-performance versions depend on rare-earth elements.

**Physical AI:** Artificial intelligence embodied in machines that sense and act in the real world.

**Precision Reducer (Harmonic or Strain Wave Reducer):** A specialized gearbox that converts a motor's fast, weak rotation into the slow, strong, highly precise movement a robot joint requires.

**Predictive Maintenance:** Using sensor data to service equipment shortly before it is likely to fail.

**Programmable Logic Controller (PLC):** The rugged industrial computer that sequences and controls machinery on a production line.

**Quadruped:** A four-legged robot.

**Rare-Earth Elements:** A group of seventeen metals used in high-performance magnets and electronics.

**Robot Cell:** The complete engineered workstation built around a robot, including safety perimeters.

**Robot Density:** Robots installed per 10,000 manufacturing employees.

**Robotics-as-a-Service (RaaS):** A subscription arrangement in which a manufacturer leases robots while the provider owns the hardware and handles integration and maintenance.

**Small- and Medium-Sized Manufacturer (SMM):** A manufacturer that is small or medium in size; exact definitions vary by country, industry, and organization.

**Standards Development Organization (SDO):** A body that convenes industry, academic, and regulatory experts to write the technical and safety standards products are built and certified against.

**Sub-Tier Supplier:** A supplier to a company's supplier.

**System Integrator:** A specialist firm that integrates a robot into a factory or manufacturing process.

**Tactile and Force-Torque Sensing):** Sensors that let a robot feel, detecting contact, pressure, and how hard it is pushing or twisting.

**Testbed:** A shared facility where new robotic systems can be trialed under realistic conditions before being committed to a live production line.

**Tooling:** The custom molds, dies, jigs, and fixtures a factory must build before it can produce a specific part.

**Total Cost of Ownership (TCO):** The full lifetime cost of a robot including integration, operator training, maintenance, downtime, spare parts, financing interest, warranty, field service, and security compliance.

**Unstructured Environment:** A workspace that is not tightly controlled or predictable.

**Upskilling / Reskilling:** Upskilling teaches existing workers new capabilities for the job they already hold; reskilling trains them for a different job entirely.

# Form Factor Finance Research

## Intro and Purpose

The American robotics venture capital landscape is undergoing a rapid expansion. In recent years, following advancements in AI, VC deal activity in robotics has spiked. Capital is flowing into the sector at record rates.<sup>137</sup> Even so, the Commission must better understand the nature of this activity to provide informed policy recommendations in its final report.

To that end, this research investigates the distribution of that venture funding, specifically the concentration of funding for humanoid robots and new software, compared with other form factors and products. This analysis does not judge the appropriate distribution; it provides a clearer picture of the status quo.

## Data

The data for this analysis is sourced from PitchBook's extensive startup database.<sup>138</sup> The database was queried for U.S.-headquartered, venture-backed companies in robotics and robotics-related industries. SCSP then further filtered the data to exclude companies that were primarily focused on drones, military systems, or self-driving cars. The firms were then sorted into one of the following categories:

1. Humanoid Robots
2. Quadruped Robots\*
3. Warehouse Robots
4. Industrial Robots
5. Medical and Lab Robots
6. Retail Robots
7. Space Robots\*
8. Robot Software

\* Only one company was categorized as either Space or Quadruped robots, and both were removed from aggregate visuals. They remained part of the data analysis. While some of these categories overlap (e.g., humanoid robots designed for warehouses), if a company fell into multiple of these categories, it was placed into the category higher on the list. For example, any company building humanoids was

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<sup>137</sup> Ali Javaheri, [Robotics & Physical AI VC Trends](#), PitchBook (2026).

<sup>138</sup> [PitchBook's Research Process](#), PitchBook (Accessed 2026).

categorized as a humanoid company, regardless of the use case. Robot software companies were only categorized as such if they did not produce their own robotic hardware. “Retail Robots” refers to robots designed either to be sold directly to end consumers for household use (such as a robot vacuum), or robots that interact directly with an end consumer (for example, one company makes a robot tattooist).

Importantly, this dataset only included venture-backed companies that had not “exited,” meaning the companies have not been acquired by another company or undergone a merger, have not gone public through an IPO, and have not gone out of business and liquidated their assets.

This process yielded 625 company observations with sufficient fidelity for analysis. The analysis focused primarily on differences in total funding for humanoid and software companies. It also examined differences in last-round size and how they changed over time. Summary statistics appear below.

| STATISTIC           | N   | MEAN     | ST. DEV. | MIN   | MAX      |
|---------------------|-----|----------|----------|-------|----------|
| Total Raised        | 625 | 50.96    | 213.21   | 0.01  | 2,345.00 |
| Last Financing Size | 446 | 29.93    | 131.79   | 0.01  | 1,500.00 |
| Year Founded        | 625 | 2019.52  | 5.19     | 1,972 | 2,026    |
| Last Financing Year | 625 | 2,024.49 | 1.72     | 2,017 | 2,026    |
| Humanoid Robots     | 625 | 0.03     | 0.17     | 0     | 1        |
| Robot Software      | 625 | 0.20     | 0.40     | 0     | 1        |

## Methodology

In addition to examining aggregate statistics, we performed two regressions for this analysis. The first regression looked at the relationship between total funding a company has received and the primary form factor of the company’s products. The regression used the following model:

$$1. TotalFunding = \beta_0 + \beta_H Humanoid + \beta_S Software + \{\beta_n\} \cdot \{Controls\}$$

In this model *Humanoid* and *Software* are binary indicator variables denoting whether a company is a humanoid robot or a robot software company (these categories are exclusive).  $\beta_H$  represents the difference in expected funding between humanoid and non-humanoid, non-software robotics companies, holding the model's controls constant.  $\beta_S$  represents the corresponding difference between software and non-humanoid, non-software companies.  $\{Controls\}$  represents a vector of binary indicator variables representing the year a company was founded and the year of its last financing round.

The second regression looked at the relationship between the size of a company's last financing round and the company's primary product form factor and last funding year, while explicitly testing whether funding trends over time differ depending on the type of company. It used the following regression model:

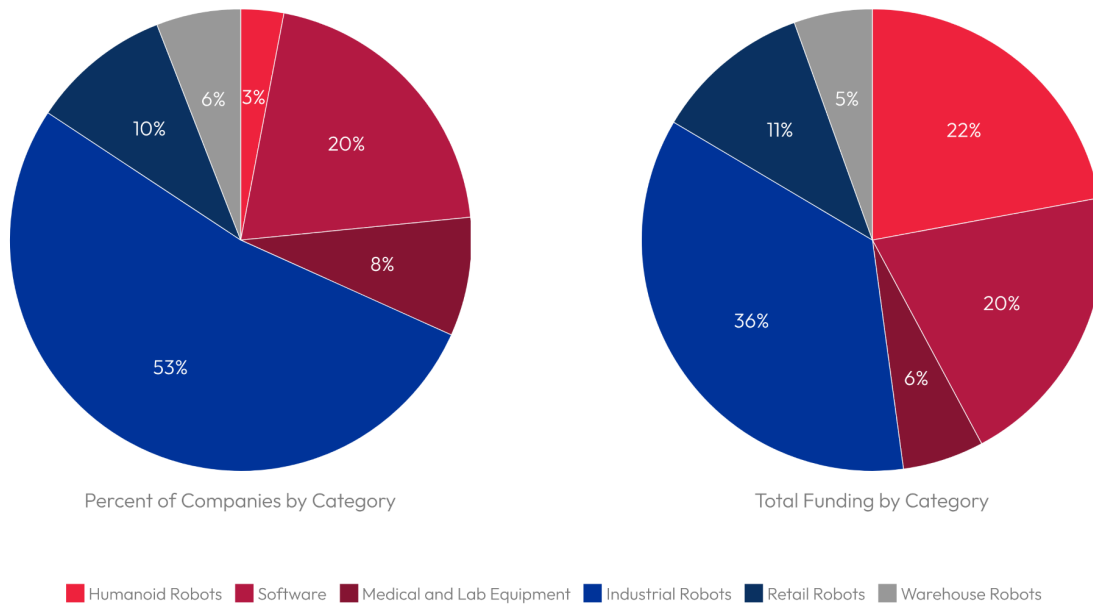
$$2. LastFinancingSize = \delta_0 + \delta_H Humanoid + \delta_S Software + \delta_Y \{LastFinancingYear\} + \delta_{H,Y} Humanoid \cdot \{LastFinancingYear\} + \delta_{S,Y} Software \cdot \{LastFinancingYear\} + \{\delta_n\} \cdot \{Controls\}$$

Unlike model 1, this model includes the interactions between *Humanoid* and *Software* and  $\{LastFinancingYear\}$ , or the set of binary indicators representing the last financing year. The  $\{Controls\}$  vector again includes binary indicators for the year the company was founded.  $\delta_H + \delta_{H,Y}$  represents the expected difference in last-financing size for a humanoid company in year  $Y$  compared to a non-humanoid, non-software company in year  $Y$ .  $\delta_S + \delta_{S,Y}$  represents the expected difference in last financing size for a software company in year  $Y$  compared to a non-humanoid, non-software company in year  $Y$ . Fewer observations were available for this regression as not all companies had the last financing round size included.

## Results

Aggregate statistics show that humanoid companies accounted for roughly 22% of the total funding, yet they only accounted for 3% of the total companies. Funding was more proportionate to company counts in other categories, except for the industrial-robot category, which received a substantially smaller share of total funding compared to its portion of total companies (35.7% of funding compared to 52.5% of companies).

## Funding and Company Share by Product Form Factor



Both regressions also found statistically significant results. Regression 1 found that humanoid firms received an estimated \$192.8 million more in funding than non-humanoid, non-software robot firms all else equal, with a p-value below 0.01. There was no statistically significant difference for software robot firms.

## Regression 1 Results

| DEPENDENT VARIABLE:  |                                   |
|----------------------|-----------------------------------|
| Millions USD         |                                   |
| Total Funding Raised |                                   |
| Humanoids            | 192.821***<br>(52.801)            |
| Software             | 21.291<br>(22.664)                |
| Constant             | 9.606<br>(277.521)                |
| Controls             | Year Founded, Last Financing Year |
| Observations         | 625                               |
| R2                   | 0.071                             |
| Adjusted R2          | 0.010                             |
| Residual Std. Error  | 212.110 (df = 586)                |

NOTE: \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

Regression 2 found that humanoid companies had last-round financing amounts an estimated \$247.48 million and \$312.66 million greater than non-humanoid and non-software robotics companies in 2025 and 2026, respectively, and all else equal, which represent just under and just over two standard deviations. Both of those results were statistically significant with a p-value below 0.01. There were no other statistically significant results.

## Linear Combinations by Year: Humanoid vs. Software

| YEAR | HUMANOID             | SOFTWARE          |
|------|----------------------|-------------------|
| 2018 | N/A                  | 6.00<br>(156.93)  |
| 2019 | N/A                  | N/A               |
| 2020 | -21.28<br>(139.38)   | 2.48<br>(88.63)   |
| 2021 | N/A                  | -8.76<br>(76.41)  |
| 2022 | 7.23<br>(134.43)     | -1.67<br>(55.50)  |
| 2023 | N/A                  | -8.12<br>(71.34)  |
| 2024 | 17.49<br>(131.84)    | -13.90<br>(50.25) |
| 2025 | 247.48***<br>(51.55) | -0.38<br>(34.95)  |
| 2026 | 312.66***<br>(69.97) | 34.01<br>(26.16)  |

Standard errors in parentheses. \* p<0.1; \*\* p<0.05; \*\*\* p<0.01.

N/A indicates years in which no companies in the data of the relevant form factor received financing.

## Interpretation

These results indicate that humanoid companies receive a disproportionate share of robotics venture funding, with the second regression indicating that the disparity is particularly acute in the last two years. There are some limitations to these results.

In particular, because the dataset only includes companies that have not “exited” through various mechanisms including going out of business, the regression results could

be explained if humanoid companies need greater capital to survive or are more likely to go out of business.

Under either assumption, we would expect to see far fewer humanoid companies included in our data, and we would be much more likely to see humanoid companies that had successfully raised large amounts of capital in the dataset. This would also explain the premium in financing size of humanoids in the last two years, as under these assumptions, the companies contributing to that data would be more likely to be raising later-stage rounds, which are typically larger.

These assumptions are further supported by the small number of humanoid companies, which are on average younger than the non-humanoid companies, with a mean two years younger, and a median four years younger. This would not, however, explain the disproportionate share of total funding attributable to humanoid companies. Under these same assumptions, we would expect the aggregate data to be underestimating the total funding humanoid companies receive in comparison to other robotics companies.

## **Conclusion and Discussion**

This report finds that humanoid robotics companies receive a disproportionate amount of venture and early-stage capital compared to non-humanoid robotics companies. There are many potential explanations for this. As an emerging technology, humanoids may receive more attention from early-stage investors, while other, more developed, areas of robotics may receive capital through other mechanisms. In such a case, it would be natural for humanoids to be more dominant in the robotics venture capital ecosystem. Alternatively, investment in humanoids may be driven by market narrative and speculative enthusiasm more than immediate commercial fundamentals. A combination of both effects could also be at play.

# Wage Trend Research

## Methodology: Combining CES Industry Trends with OEWS Occupation Benchmarks

This appendix documents the methods behind the report's wage figures. The analysis has three stages. First, it compares all-employee and production-and-nonsupervisory average hourly earnings in manufacturing to remove the upward skew introduced by managers, engineers, and administrative staff. Second, it tracks manufacturing production-and-nonsupervisory earnings against the corresponding CES series for five other sectors. Third, it compares May 2025 OEWS using entry- and senior-level wage percentiles for six selected frontline occupations. Together, these stages describe changes in observed wage differentials; they do not estimate a wage premium adjusted for worker characteristics.

### Data sources

Two Bureau of Labor Statistics (BLS) survey programs anchor the analysis.

- The Current Employment Statistics (CES) survey supplies monthly average hourly earnings by industry and worker category, enabling the time-series comparisons.
- The May 2025 Occupational Employment and Wage Statistics (OEWS) survey supplies occupation-level wage distribution for the cross-sectional comparison.

CES does not report occupation-level wages, while OEWS provides an annual cross-section rather than a monthly time series. The analysis therefore uses CES to assess industry trends and OEWS to compare selected occupations at one point in time; the datasets are complementary but are not directly merged. CES nominal earnings are deflated with the CPI-U and expressed in January 2000 dollars, consistent with the figures.

### Methodology

*Real-wage construction.* The analysis compares two CES manufacturing series, both deflated with the same CPI-U index: average hourly earnings for all employees and average hourly earnings for production and nonsupervisory employees. The gap between the series reflects differences in the workers included in each average; it should not be interpreted as a causal estimate of the effect of managers, engineers, or administrative staff on pay. The production-and-nonsupervisory manufacturing series

is then compared with the corresponding series for construction; retail trade; transportation and warehousing; education and health services; and leisure and hospitality.

*Occupational benchmark selection.* CES reports by industry; OEWS reports by occupation. Because there is no one-to-one mapping, the OEWS comparison uses one illustrative frontline occupation for each CES sector rather than statistically linking the datasets. The selection proceeds in two steps.

1. Each CES sector is associated with the two-digit SOC major group that most closely represents its frontline workforce—for example, Production Occupations (SOC 51-0000) for manufacturing.
2. Within each major group, one nonmanagerial occupation is selected using two criteria: no typical four-year-degree requirement and work representative of a substantial frontline segment of the sector. The comparison excludes management, engineering, and office and administrative support occupations. The resulting six benchmarks and the inclusion and exclusion rules are listed in the table below.

**Percentile benchmarks.** Two May 2025 OEWS percentiles are reported for each benchmark occupation: the 25th percentile—the applied convention for approximating entry-level pay, and the 90th percentile—the standard benchmark for senior or experienced workers within a non-managerial occupation. Applied consistently across the six selected occupations, they support a comparison of lower- and upper-end pay in those roles.

## Interpretation and Limitations

The CES comparisons are descriptive averages, not regression-adjusted estimates. They do not control for differences in worker education, experience, occupation mix, geography, union coverage, or other factors that can affect wages. The OEWS comparison likewise reflects selected occupations at one point in time (May 2025). The analysis therefore supports a narrower conclusion: manufacturing’s observed wage advantage over several frontline alternatives has narrowed; it does not by itself establish why the change occurred or the size of an adjusted manufacturing wage premium.

| CES INDUSTRY                            | OEWS MAJOR GROUP                                                     | KEY BENCHMARK OCCUPATION                                | INCLUDES                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | EXCLUDES                                                                                                                                                                                                                                                                                                                                                             |
|-----------------------------------------|----------------------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Manufacturing</b>                    | <b>SOC 51-0000</b><br>Production Occupations                         | <b>SOC 51-2000</b><br>Assemblers and Fabricators        | <ul style="list-style-type: none"> <li>Team assemblers (the largest single component; rotate across assembly-line tasks)</li> <li>Aircraft structure, surfaces, rigging &amp; systems assemblers</li> <li>Electrical, electronic &amp; electromechanical equipment assemblers</li> <li>Engine and other machine assemblers</li> <li>Structural metal fabricators and fitters</li> <li>Fiberglass laminators and fabricators; timing device assemblers/adjusters</li> </ul> | <ul style="list-style-type: none"> <li>Welders, solderers, and brazers (SOC 51-4120)</li> <li>Machinists and machine setters/operators who cut or shape material (SOC 51-4000s)</li> <li>Quality-control inspectors, when that is their primary duty (SOC 51-9061)</li> <li>Production supervisors (SOC 51-1000s) and industrial engineers (SOC 17-0000s)</li> </ul> |
|                                         | <b>SOC 47-0000</b><br>Construction & Extraction Occupations          | <b>SOC 47-2061</b><br>Construction Laborers             | <ul style="list-style-type: none"> <li>Excavation and site preparation</li> <li>Material handling and staging</li> <li>Erecting/dismantling scaffolding and bracing</li> <li>Concrete mixing, pouring, and finishing</li> <li>Assisting skilled trades with prep work</li> </ul>                                                                                                                                                                                           | <ul style="list-style-type: none"> <li>Licensed trades — electricians, plumbers, carpenters, HVAC technicians, operating engineers[3]</li> <li>Construction supervisors and managers</li> </ul>                                                                                                                                                                      |
| <b>Retail Trade</b>                     | <b>SOC 41-0000</b><br>Sales & Related Occupations                    | <b>SOC 41-2031</b><br>Retail Salespersons               | <ul style="list-style-type: none"> <li>Direct-to-consumer sales and product demonstration</li> <li>Processing transactions and returns</li> <li>Stocking and arranging merchandise displays</li> </ul>                                                                                                                                                                                                                                                                     | <ul style="list-style-type: none"> <li>Cashiers, whose primary duty is payment rather than sales (SOC 41-2011)</li> <li>Retail supervisors; wholesale/B2B sales representatives</li> <li>Licensed sales occupations — real estate, insurance, and securities agents</li> </ul>                                                                                       |
| <b>Transportation &amp; Warehousing</b> | <b>SOC 53-0000</b><br>Transportation & Material Moving Occupations   | <b>SOC 53-7065</b><br>Stockers and Order Fillers        | <ul style="list-style-type: none"> <li>Receiving, storing, and issuing stock</li> <li>Inventory checks and price marking</li> <li>Order picking and packing</li> </ul>                                                                                                                                                                                                                                                                                                     | <ul style="list-style-type: none"> <li>Truck and delivery drivers</li> <li>Warehouse supervisors</li> <li>Laborers and Material Movers, Hand — general freight handling (SOC 53-7062, a separate code)</li> </ul>                                                                                                                                                    |
| <b>Education &amp; Health Services</b>  | <b>SOC 31-0000</b><br>Healthcare Support Occupations                 | <b>SOC 31-1120</b><br>Home Health & Personal Care Aides | <ul style="list-style-type: none"> <li>In-home / residential direct care: bathing, dressing, feeding, mobility assistance</li> <li>Medication reminders and vital-sign monitoring</li> <li>Light housekeeping and companionship</li> </ul>                                                                                                                                                                                                                                 | <ul style="list-style-type: none"> <li>Nursing Assistants — institutional setting, closer clinical supervision (SOC 31-113)</li> <li>Licensed practical and registered nurses (both require licensure)</li> <li>All SOC 25-0000 teaching occupations (bachelor's degree required)</li> </ul>                                                                         |
| <b>Leisure &amp; Hospitality</b>        | <b>SOC 35-0000</b><br>Food Preparation & Serving Related Occupations | <b>SOC 35-3023</b><br>Fast Food and Counter Workers[4]  | <ul style="list-style-type: none"> <li>Counter/register order-taking and payment processing</li> <li>Simple, ready-to-serve food and beverage preparation</li> </ul>                                                                                                                                                                                                                                                                                                       | <ul style="list-style-type: none"> <li>Cooks, who require more food-prep skill and experience (SOC 35-2000s)</li> <li>Waiters and waitresses — table service, typically tip-based (SOC 35-3031)</li> <li>Bartenders, food service supervisors</li> </ul>                                                                                                             |