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Citi GPS

The Rise of AI Robots

Physical AI is Coming for You

Citi GPS: Global Perspectives & Solutions

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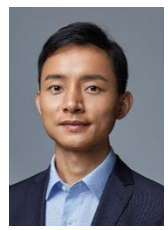

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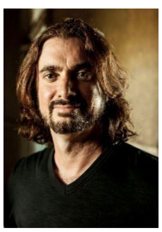

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THE RISE OF AI ROBOTS

Physical AI is Coming for You

We are entering a new era in which AI-robots and humanoids will be moving all around us. Our analysis suggests there will likely be 1.3bn AI-robots by 2035 and 4bn by 2050.

Jensen Huang, CEO of NVIDIA, recently stated that "the next wave of AI is here. Robotics, powered by physical AI, will revolutionize industries.[1]" Elon Musk, CEO of Tesla, said the market for one form or robot—humanoids-- could exceed 1bn units per year and that we will eventually have more robots than humans.[2]

There are 3 primary drivers of this new market:

1. Technology – multiple technological advances, especially in Artificial Intelligence (AI) have dramatically changed the outlook for robots.
2. Economics – Robots can provide solutions to labor shortages. Shortages are exacerbated by aging demographics and more restrictive immigration policies. In addition, the payback period for capable robots looks increasingly attractive versus humans. Labor accounts for over 50% of GDP globally. So the market opportunity could be enormous.
3. Betterment – Technological progress has freed people up from mundane tasks and increased leisure time. Continuing this trend AI-robots will offer people access to robotic cleaners, butlers, chauffeurs, assistants, and carers.

Exploring these drivers, this report is organized into 3 primary sections:

1. Technology – we highlight 9 changes in Chapter 1. The most significant come from advancements in AI allowing robots to see, to learn, to move, to talk, to take instruction into code and then actions. Only recently has multi-modal AI allowed all these elements to fit together. AI in turn is becoming embodied and physical. In parallel have been advancements in dexterity. Some robots can now thread a needle or suture a kernel of corn. Robots are on the move, from theory to reality and from useless to useful.
2. Use cases – static robots are also growing, but the focus of this report is on AI-enabled robots that move. Chapters 2-8 look at potential use cases for AI-robots, from cleaning, to driving, to delivery, to use in industrial, construction, retail, hospitality, and care sectors. Our proprietary analysis of 9 uses case areas forecasts 4.1 billion robots by 2050. For one use case, humanoids, we further break this down into 7 areas. Our methodology is summarized next.
3. Challenges – Chapter 10 looks at 12 challenges that deserve attention, debate and solutions.

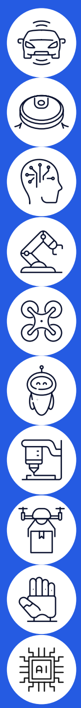
Despite the challenges, we conclude that a huge new (non-human) market is being born. And that AI-robots are coming for you.

[1] NVIDIA CEO Jensen Huang Keynote at COMPUTEX 2024
[2] Bloomberg Technology - Elon Musk Says There will be more robots than people by 2040

The Rise of AI Robots

Physical AI is Coming For You

We forecast that 1.3 billion AI Robots will be moving around us by 2035, and 4 billion by 2050. The three primary drivers of this will be technology, economics and betterment. Here are some of the numbers on the rise of the robots.



Robot Unit Number (Millions) Forecast by Type

Source: Citi GPS

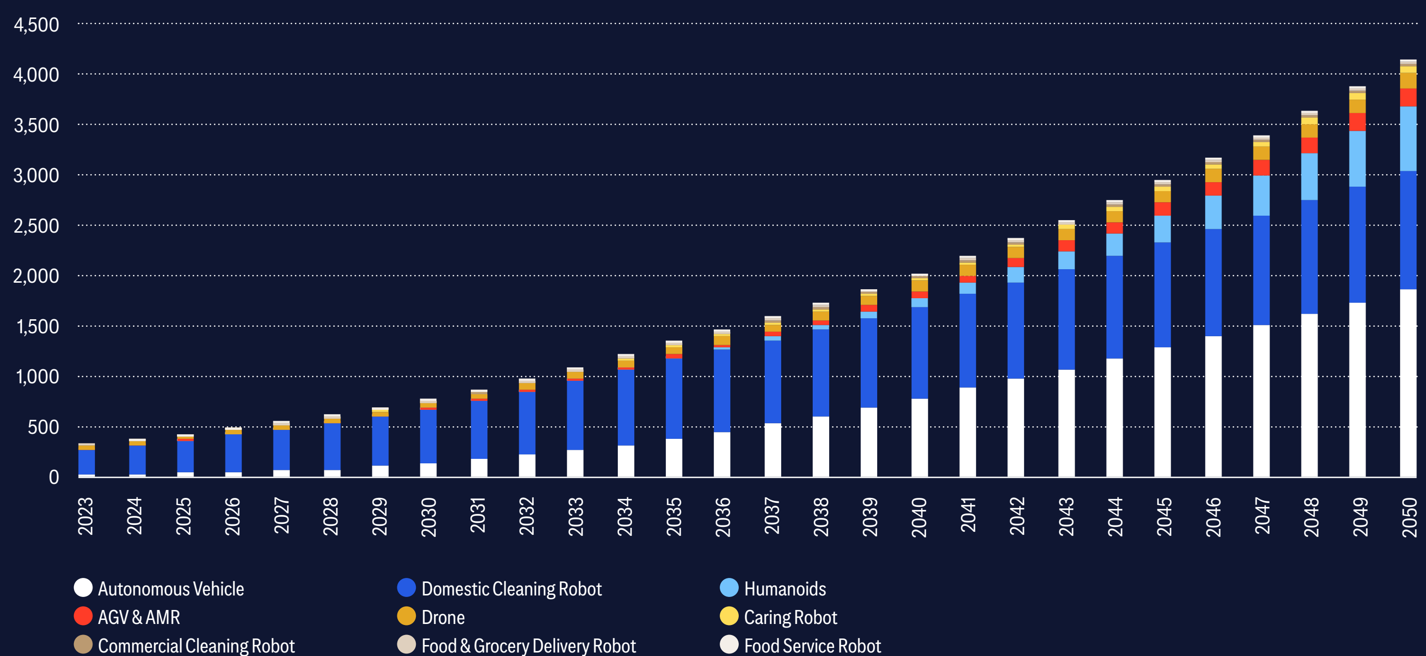
	2024	2025	2030	2035	2050	CAGR
Autonomous Vehicle	27	34	126	380	1,858	17.4%
Domestic Cleaning Robot	286	326	541	793	1,188	5.3%
Humanoids	0	0	1	13	648	60.7%
AGV & AMR	2	3	9	28	181	17.7%
Drone	37	40	54	73	149	5.4%
Caring Robot	0	1	6	18	71	20.0%
Commercial Cleaning Robot	1	2	6	14	25	10.6%
Food & Grocery Delivery Robot	0	0	4	11	19	19.2%
Food Service Robot	0	0	3	10	15	17.2%
Caring Overlap	0	0	(1)	(5)	(18)	
Total	354	405	749	1,337	4,136	9.7%

Humanoid Payback Period Sensitivity Table (in weeks)

	Humanoid price ($)	15,000	20,000	25,000	30,000	35,000
Hourly wage	7.25	21.6	28.7	35.9	43.1	50.3
	16.00	9.8	13.0	16.3	19.5	22.8
	28.00	5.6	7.4	9.3	11.2	13.0
	41.00	3.8	5.1	6.4	7.6	8.9

Robot Unit Number Forecast by Type

Source: Citi GPS



Contents

Summary and Analysis

AI is not new (1950s). Robots are not new (1960s). Moving AI-robots are.

In the last decade big leaps forward in AI are allowing robots to see, move, talk, learn, and act. We cover 9 of these technological advances in Chapter 1 of this report. Chapters 2-8 look at different use case and developments of AI-robots.

Arguably one of the most complicated areas is AVs (Autonomous Vehicles) given the high risk of AVs driving at 70 mph without supervision has meant regulatory approval has been understandably slow. This is now changing. Waymo is conducting 100,000 AV rides a week. Other trials and approvals are taking place with an opportunity to cut fatalities (1.4m people die each year in car crashes[3]), increase mobility for those who can't drive and free up people's time. Our analysis points to an estimated 1.8bn AVs by 2050.

AVs are still very expensive. At the other end of the price and risk spectrum, AI enabled robot vacuum cleaners are already whizzing around 20% of US and 9% of Chinese households. Our analysis suggests 1.2bn household and 25m commercial cleaning robots by 2050.

The newest robot category is humanoids. These are designed to fit into man-made environments and offer versatility across many tasks. When analyzing the opportunity for humanoids we see the most promise firstly in industrials (i.e. manufacturing and warehouses) and then in households. The primary functions we see in households are in cleaning and caring. While this new sector will take time to build, we see 648m units and a $7 trillion humanoid market by 2050.

One of our aims in this report was to try to size the different market opportunities for AI-Robots. The conclusion of this analysis is below. An adjustment item has been made to eliminate double counting of robots used in the care industry and humanoids helping care for elderly in their homes.

This report also features several companies that are active in this area as illustrative examples of use cases in action.

[3] https://waymo.com/about/

Figure 1. Robot Unit Number (Millions) Forecast by Type

	2024	2025	2030	2035	2050	CAGR
Autonomous Vehicle	27	34	126	380	1858	17%
Domestic Cleaning Robot	286	326	541	793	1188	5%
Humanoids	0	0	1	13	648	61%
AGV & AMR	2	3	9	28	181	18%
Drone	37	40	54	73	149	5%
Caring Robot	0	1	6	18	71	20%
Commercial Cleaning Robot	1	2	6	14	25	11%
Food & Grocery Delivery Robot	0	0	4	11	19	19%
Food Service Robot	0	0	3	10	15	17%
Caring Overlap	0	0	(1)	(5)	(18)	
Total	354	405	749	1,337	4,136	10%

Source: Citi GPS

Our methodology includes estimating the size of the total market in 3 regions (Developed, Less Developed, Least Developed) to cover most of the world, then applying different penetration rates for each use case and each region.

We assume less developed markets have half the penetration rate of developed regions, and the least developed have half that of less developed markets. We have analyzed the numbers for each region through 2050.

We recognize augmentation versus substitution concerns are neither uniform nor straightforward. For example, AVs will likely substitute for some driving occupations (e.g. taxis), but some driving occupations involve other tasks/services (e.g. delivery).

Adoption and penetration rates will vary based on economics. We find that the opportunity in cleaning appears sizeable (Table 1 showing 1188m cleaning robots forecast suggests the opportunity for adoption in cleaning is substantial). A surprise when looking at humanoids was the payback period appears extraordinarily short when benchmarked versus minimum wages in the US ($7.25), in California ($16.00), versus factory workers (US average $28), or nurses ($41.00), as shown in the figure below[4].

Figure 2. Humanoid Payback Period Sensitivity Table (in weeks)

Hourly Wage ($/h) \ Humanoid Price ($)	15,000	20,000	25,000	30,000
7.25	21.6	28.7	35.9	43.1
16	9.8	13.0	16.3	19.5
28	5.6	7.4	9.3	11.2
41	3.8	5.1	6.4	7.6

Source: Citi GPS

[4] The Rise of AI Robots - Humanoids are Coming for You

Within humanoids, we estimate 2050 penetration rates of 30% / 20% / 10% for industrial settings in Developed / Less / Least regions. We estimate 22% / 11% / 5% for households. Our household estimates are influenced by elderly population sizes (>80) and those who have cleaners[5]. Given caring and cleaning robots will likely benefit many others, it is possible our penetration rate assumptions prove too low. We also note that we have not analyzed several large potential markets – such as military, safety, security, education, agriculture.

While adoption is expected to be higher for most developed regions, we conclude that less developed regions will account for a significant portion of the overall market by 2050 given the size of their populations and labor markets. The figure below suggests less developed regions will account for two-thirds of the humanoid market by 2050.

Figure 3. Humanoid Analysis Breakdown by Development Group (in mn units)

Development Group	2035	2050	CAGR
More developed regions	8.0	181.2	23%
Less developed regions	5.3	433.1	34%
Least developed regions	0.0	33.8	62%
Total	**13.3**	**648.1**	**30%**

Source: Citi GPS

We also note that VC investment into robots in Asia has been rising and that as measured by patents, robot innovation is booming in Asia. The US may be leading the world in areas of AI, but our proprietary analysis shows China has accounted for 78% of all robotics patents over the past two decades.

Google's chief economist Hal Varian once said, "a simple way to forecast the future is to look at what rich people have today.[1]" In previous generations this included running water, flushing toilets, cars, washing machines, post-primary education, or music on demand. As we discussed in our AI Assistants report last year, AI can bring personal assistants, coaches, infinitely patient education tutors and health coaches to many. As noted in this report, AI robots can also offer people cleaners, butlers, chauffeurs, and carers. With appropriate cost, capabilities and guardrails, demand for these services could be very significant.

Recent Generative AI advances are pointing at cognitive tasks or creating art on demand. What many people really want is help with mundane tasks, such as cleaning, so they can do more thinking, art, and leisure. AI robots can help with this utopian angle.

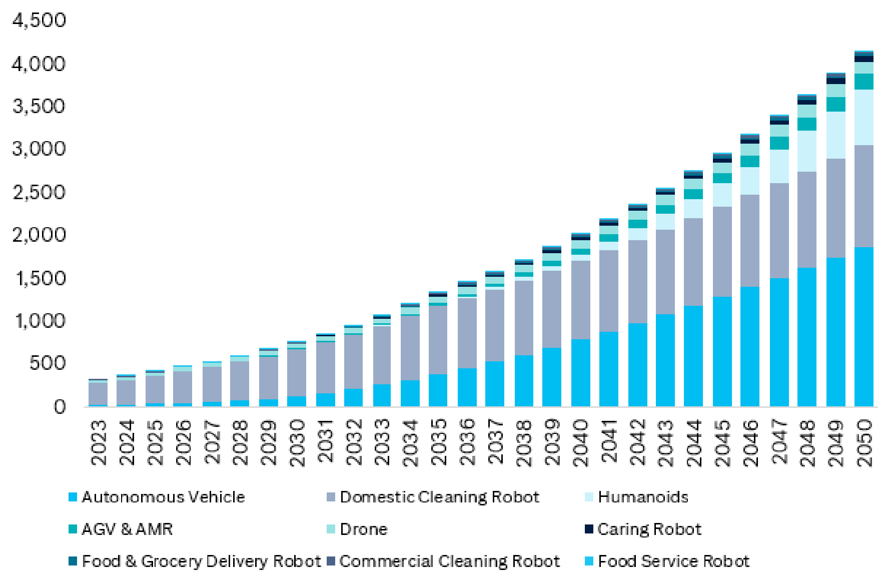
There is of course a more dystopian fear of robots substituting jobs, as discussed in the challenges chapter. The subtitle of this report however that 'AI-Robots are coming for you' is a nod to another potential outcome. AI feeds from your data and can add more value to you the more it learns about you. Proprietary data is a competitive advantage. The same may be the case for personalized AI robot assistants. The evidence of most digitizing businesses over the last 30 years has

[5] The Rise of AI Robots - Humanoids are Coming for You
[1] https://www.ft.com/content/4329a987-9256-3059-b36f-1aba9338b800

been a market share race towards winner-takes-most economics. If this was to happen in AI-robots it would accelerate adoption.

When we add this data point to the technological, economic and betterment drivers, we believe ‘AI-Robots are Coming for You’. As a result, we estimate 4 billion AI-robots may be moving around us by 2050. This conclusion is shown below and explained in more detail in this report.

Figure 4. Robot Unit Number Forecast by Type



Source: Citi GPS

Technological Advancements

Equipped with AI, robots can increasingly navigate complex environments, make autonomous decisions, and adapt to changing conditions, and thus bridge the gap between AI and physical activities.

This embodiment of AI will allow robots to undertake increasing roles in industries such as manufacturing, healthcare, and beyond – transforming the software advancements we so often hear about into practical applications.

In recent years, significant advancements in AI and related technologies have driven the development of next-generation robotics, transforming them into intelligent, autonomous systems to revolutionize various sectors.

Ingmar Posner
Professor of Applied Artificial Intelligence
Department of Engineering Science
Oxford University

Where have we seen technological progress for AI Robots?

Robotics has advanced rapidly in recent years, both in terms of the availability of robust and rugged platforms as well as in terms of capability. Robots like Boston Dynamics' Spot and ANYbotics' ANYmal have developed into reliable, versatile tools, now commonly used in inspection, surveillance, and search and rescue in challenging settings. The technological advances in control, planning and machine learning approaches that have enabled this shift are now increasingly being deployed towards a new generation of humanoid robot platforms.

Similarly, advances in machine learning for robotics have led to capable robot manipulators able to perform tasks of increasing value to industry and the public domain. Progress in manipulation and dexterity has been steady and, while they are far from solved, advances in capability are allowing mobile manipulation to rapidly come into focus as an upcoming key frontier. The advent of large language models holds promise to bridge one of the foundational challenges in AI: the availability of common sense, general knowledge. While these models for now lack an explicit ability to reason, they can already serve as a backbone for robot perception, action, and interaction.

Looking at to the next 3-5 years, which areas of technological progress are you most optimistic or pessimistic about?

The rapid development in humanoid robotics hardware will undoubtedly continue at pace, though it is unclear how far these systems will be able to progress in that timeframe beyond basic capabilities such as locomotion and pick-and-place tasks. Endowing large, pre-trained models with an explicit ability to reason remains a frontier in AI and will unlock broader deployments of this technology in robotics, where agents act and interact in the physical world. Model size and a model's energy footprint in training and inference remain one of the principal bottlenecks when it comes to deploying recent large models in robotics, where systems are typically resource constrained. I look forward to seeing more exciting developments in those spaces. I am a technology enthusiast and I believe that robotics, machine learning and AI more generally hold promise to allow us to solve some of the most pressing challenges of our time. However, the use of this technology for causes detrimental to society, such as misinformation and warfare remains a significant concern. It will require a concerted effort of technology developers, legislators and society as a whole to turn this most recent technological revolution into a success for all of us.

1. Foundational Models

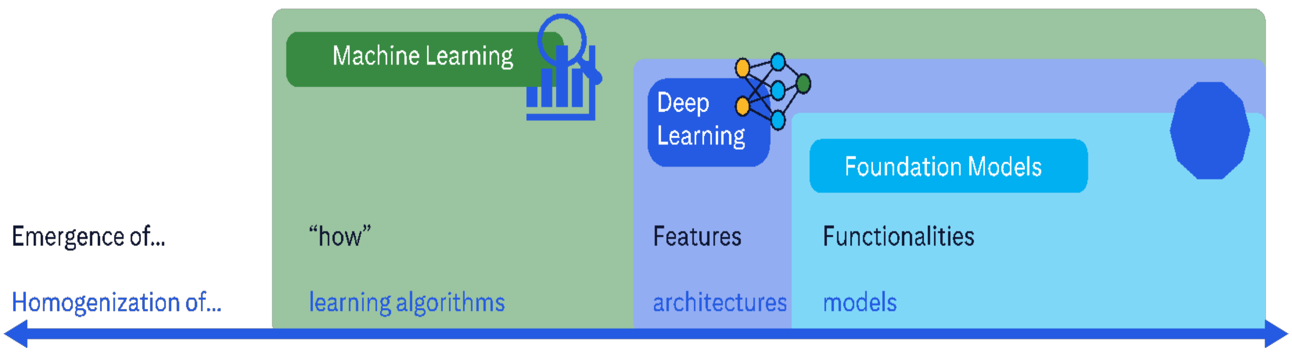
Reinforcement learning is an area of machine learning that allows AI models to learn how to makes decisions, often in new and dynamic environments.

The advent of a “transformer” based architecture, introduced by Google in 2017, revolutionized the field of AI and is poised to do the same for robotics. It represented a fundamental shift in how AI systems are designed and trained. Instead of relying on labelled datasets, transformers can learn from unstructured and unlabelled data, making them far more versatile and powerful.

This innovation has enabled AI models to scale up dramatically, with the size of these models increasing by 32,000x in just under 5 years.

A foundational model, as defined by Bommasani et al. (2021), is “any model trained on broad data (generally using self-supervision at scale) that can be adapted (e.g., fine-tuned) to a wide range of downstream tasks.”

Figure 5. The Story of AI Has Been One of Increasing Emergence and Homogenization



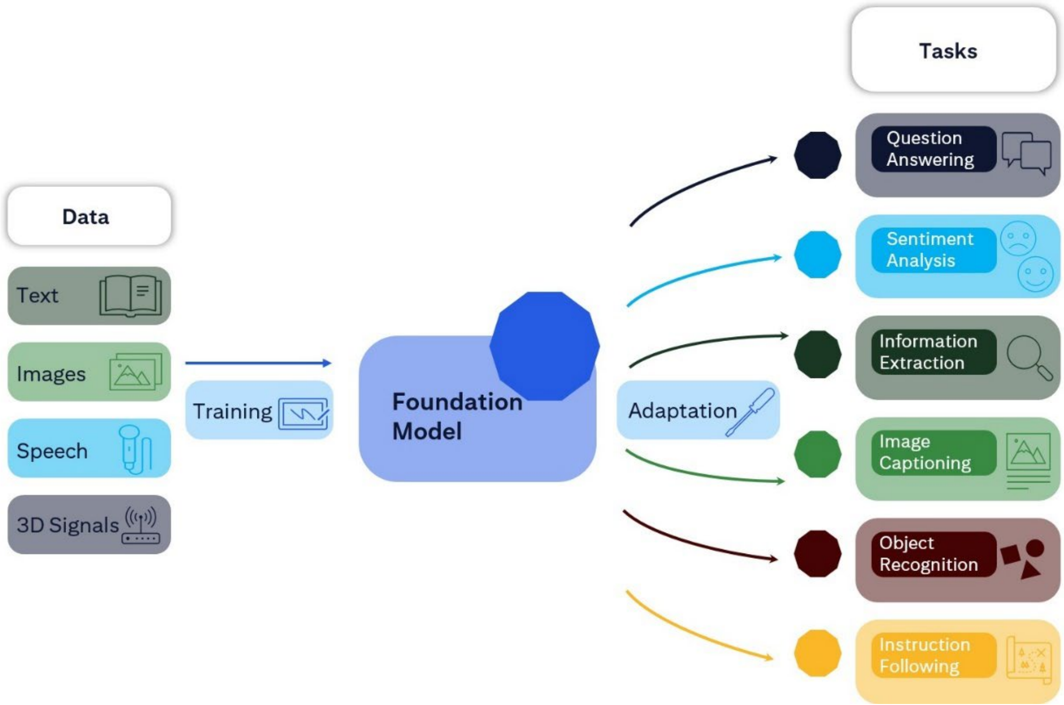
Source: On the Opportunities and Risks of Foundation Models

The implications of foundational models for robotics are profound. They can take a task description, convert it into executable code, and then translate this into physical actions by the robot. This capability could democratize access to advanced robotics.

2. Multimodality

Multimodality involves the integration of various AI techniques to enhance a robot's ability to perceive, interpret, and interact with its environment. This approach involves the convergence of different AI capabilities. This convergence is greater than the sum of its parts, addressing the limitations of earlier models that often operated in siloes. Multimodal AI allow robots for to have a more comprehensive understanding of their environment and to complete more complex tasks.

Figure 6. The Story of AI Has Been One of Increasing Emergence and Homogenization



Source: On the Opportunities and Risks of Foundation Models

The concept of multimodality in AI gained considerably mainstream traction in the last year with the development of advanced models like OpenAI's GPT-4 and Google's Gemini.

Early natural language processing (NLP) models often struggled with context, producing sentences that lacked coherence and subtlety. This was a significant hurdle in developing robots that could understand and respond to complex instructions or engage in meaningful interactions.

In 2020, OpenAI's GPT-3 achieved a 22% improvement over its predecessor, GPT-2, in human-level performance on various language tasks, including reading comprehension and text completion. This leap forward was followed by the development of GPT-4, which now for example outperforms humans in answering medical examination questions.

Speech recognition is another critical component of multimodal AI, particularly for robots that need to interact with humans intuitively. In 2017, Microsoft's speech recognition system hit a word error rate (WER) of 5.1%, matching the performance of human transcribers. More recent models, such as Google's WaveNet, are more accurate than humans in certain scenarios.

AI has made remarkable progress in computer vision, enabling robots to navigate and interact with their physical environments. The field saw a significant breakthrough in 2012 with the introduction of AlexNet, a deep learning model that drastically reduced the image classification error rate to 15%, effectively jump-starting the modern era of deep learning in computer vision. This progress continued with Microsoft's ResNet in 2015, which achieved a 3.6% error rate, surpassing the estimated 5-10% error rate for humans.

Today, computer vision systems in robots are capable of near-perfect accuracy in specific applications, such as facial recognition and autonomous navigation.

In addition to processing visual and auditory signals, robots must also be able to understand and navigate 3D environments. While humans rely on a combination of visual and auditory cues to perceive 3D spaces, robots can be equipped with dedicated sensors that provide a more detailed understanding of their surroundings.

One such technology is Light Detection and Ranging (LIDAR), which has seen significant reductions in cost over the past decade, making it more accessible for use in robotics. LIDAR allows robots to undertake real-time object detection and navigation, processing 3D signals tens of times faster than humans can.

3. Dexterity

Robot development has been hindered by a phenomenon known as Moravec's paradox – that fact that it is "it is comparatively easy to make computers exhibit adult level performance on intelligence tests or playing checkers, and difficult or impossible to give them the skills of a one-year-old when it comes to perception and mobility".

Historically, robotic hands and arms were limited to performing simple, repetitive tasks, but recent breakthroughs have begun to close this gap, bringing robots closer to achieving human-like dexterity.

One noteworthy example is a project led by a team at MIT, which recently designed a highly dexterous robotic hand capable of reorienting 2,000 diverse objects with ease. This represents a substantial leap forward in the ability manipulate objects of various shapes and sizes.

One of the most iconic examples of robotic dexterity in recent years is the DaVinci surgical robot. This system gained widespread recognition in 2019 when it was showcased suturing a grape, demonstrating its precise control and delicate touch. Following this, the DaVinci robot received clearance from the U.S. Food and Drug Administration (FDA) to be used in a wide range of surgical procedures.

By 2023, over 7 million surgeries had been performed worldwide using robotic assistance, significantly reducing patient recovery times and improving surgical outcomes.

The ability to perform fine movements means that surgeons can now operate at scales that are one-tenth of what is possible using only human hands, vastly expanding the possibilities for micro-surgery and other intricate procedures.

The progression in robotic dexterity is also reflected in the increasing degrees of freedom (DOFs) that modern robots possess. Early robotic arms typically had only 3-4 DOFs, which severely limited their range of motion and flexibility. In contrast Tesla's Optimus humanoid robot, which was designed with the goal of assisting in both industrial and domestic environments, currently boasts 11 DOFs in its hands, with plans to increase this to 22 by the end of 2024.

Figure 7. Adaptable Fruit-Picking Robot

Source: Field Robotics

Figure 8. Example of Highly Dexterous Robot

Source: Shadow Robotics

Advances in tactile sensitivity are also enhancing the ability of robots to perform delicate tasks. According to Touch Lab, their fabric strips can enhance the sensitivity of robotic grippers by up to 50%, allowing robots to handle fragile objects with the same care as a human hand.

Another groundbreaking development in robotic dexterity comes from Cambridge University, where researchers have developed a "third thumb" that can be used by nearly anyone within minutes of first trying it.

The "third thumb" is an extra robotic digit that can be attached to the hand, providing users with enhanced motor capabilities that go beyond what is biologically possible.

4. New & Synthetic Data

One of the significant challenges for robot industry development has been the limited availability of real-world data to train intelligent machines. This has been a "chicken-and-egg" situation: low production volumes of robots meant fewer opportunities to collect data from real-world interactions, which in turn limited the ability to improve and develop new robotic systems.

With the advent of powerful foundational models, AI systems are now being trained on vast amounts of data from various sources, including videos of humans performing everyday tasks. Video content now accounts for a staggering 83% of all internet traffic, providing an unprecedented volume of data for AI diffusion models to analyze and learn from. Enormous hours of new video content uploaded daily serve as a rich resource for training AI models, allowing robots to learn from observing human behavior in diverse and dynamic environments, enhancing their versatility and robustness in real-world applications.

In addition to utilizing real-world video data, the robotics industry is increasingly turning to synthetic data to overcome the limitations of scarce or incomplete datasets. Synthetic data is artificially generated, often through computer simulations, rather than being collected from real-world events.

One of the most significant benefits of synthetic data is its ability to scale. For instance, the latest physics-enabled simulated 3D environments allow robotic systems, such as home assistants, to be trained at an astonishing rate of over

25,000 simulation steps per second. This represents a speed-up of 100 times compared to current simulation methods.

According to Gartner, by 2030, synthetic data is expected to completely overshadow real data in AI models.

5. Edge Computing

For robots to operate autonomously and effectively in real-world environments, they must be able to analyze data in real-time and make decisions without relying on centralized cloud-based servers. This need has led to the growing importance of edge computing, a paradigm that involves processing data closer to the source – at the "edge" of the network – rather than sending it to distant data centers for analysis. The benefits include:

Reduced Latency: By processing data locally, edge computing significantly reduces the time it takes for a robot to analyze information and make decisions. This reduction in latency is crucial for applications where real-time processing is essential. Autonomous driving is an obvious example were waiting for a response via the cloud could be fatal. Or in the industrial sector, robots monitor and optimize production lines in real-time, adjusting their actions based on sensor data and feedback from other machines.

Enhanced Data Privacy: Edge computing also helps mitigate data privacy concerns by keeping data local to the device. This reduces the need to transmit sensitive information over the network, minimizing the risk of data breaches or unauthorized access. For instance, a healthcare robot that processes patient data on-site can ensure that this information remains secure and confidential.

Improved Connectivity: In environments where network connectivity is unreliable or intermittent, edge computing allows robots to continue functioning independently of the cloud. This is particularly important for robots operating in remote locations, such as agricultural fields or disaster zones, where access to high-speed internet may be limited.

A key enabler of edge computing in robotics is the development of Neural Processing Units (NPUs), specialized hardware designed to accelerate AI computations.

The recent growth of NPU technology has been rapid. These improvements have made it feasible to deploy sophisticated AI models directly on robots.

6. Small Language Models (SMLs)

Related to edge computing, in the evolving landscape of artificial intelligence focus is increasingly shifting toward the development and deployment of Small Language Models (SLMs). SMLs share similarities with the more well-known Large Language Models (LLMs), but offer efficiency, cost-effectiveness, and adaptability qualities that are particularly valuable in the field of robotics.

One of the most significant advantages of SLMs is the reduction in the amount of data required for training, which directly translates into reduced training times and costs. For AI-enabled robots this can lead to faster deployment in the field.

Another critical advantage of SLMs is their lower energy consumption compared to LLMs. As AI models have grown in size, so too have the computational resources required to train them. For instance, GPT-3, one of the most prominent LLMs, reportedly consumed just under 1,300 megawatt-hours (MWh) of electricity during its training phase – equivalent to the annual power consumption of approximately 130 U.S. homes. Moreover, the cost of training GPT-4, which required 45 gigabytes of data, was estimated at around $100 million.

In contrast, SLMs require substantially less energy to train and operate, making them a more sustainable option for AI applications.

Beyond efficiency and energy savings, SLMs offer a high degree of customizability, allowing them to be fine-tuned for specific tasks with minimal additional training.

As Sonali Yadav, principal product manager for Generative AI at Microsoft, notes, "What we're going to start to see is not a shift from large to small, but a shift from a singular category of models to a portfolio of models where customers get the ability to make a decision on what is the best model for their scenario".

7. Self-Charging

The utility of AI robotics will be influenced by their ability to operate when needed. This requires improvements in power management, including robust and reliable charging solutions. Currently, the primary methods for recharging robots involve either manual charging by humans or manually swapping out batteries. While effective, these methods are labour-intensive and can result in downtime.

The need for a more autonomous solution is evident when considering the broader adoption of electric vehicles (EVs). A survey revealed that over 70% of respondents cited a lack of charging infrastructure as a significant barrier to adopting EVs. This analogy can be extended to robotics.

One of the challenges in developing self-charging infrastructure for robots is the diversity of battery types, charging rates, and voltages used by different robots. This diversity complicates the creation of a unified charging solution.

However, standardization efforts are already underway, with companies like WiBotic introducing technologies that could pave the way for a more cohesive charging ecosystem.

Figure 9. A Universal Self-Charging Hub

Source: Clearpath Robotics

For self-charging systems to be effective, robots must be capable of autonomously navigating to their charging stations. By equipping robots with GPS receivers and proximity sensors, they can easily locate their charging base from a distance and dock accurately to maximize wireless charging efficiency.

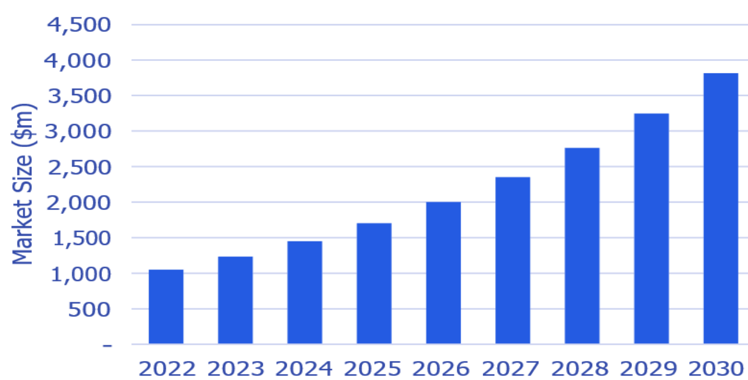
8. Robots as a Service (RaaS)

The concept of "as-a-Service" models has revolutionized numerous industries, providing businesses with scalable, flexible, and cost-effective solutions. Among these, Software as a Service (SaaS) has been particularly transformative. Initially considered a niche offering, SaaS has evolved into a massive global market, valued at approximately $3 trillion today, with projections indicating it could reach $10 trillion by 2030. The success of SaaS and similar models has paved the way for a new ‘XaaS’ entrant: Robots as a Service (RaaS).

The growth of SaaS and other "Anything as a Service" (XaaS) models is largely attributed to their cloud-native architecture, which enables the large-scale rental of virtual services as if they were physical products. This cloud-based approach allows companies to access cutting-edge software and services without the need for significant upfront investments in infrastructure or hardware. Instead, businesses can pay for these services on a subscription basis, scaling usage up or down based on their needs.

RaaS is a subscription-based business model that allows users to rent robots rather than purchase them outright. While still in its early stages, the RaaS market is already valued at approximately $2 billion and is expected to grow at a compound annual growth rate (CAGR) of 17% in the coming years.

Figure 10. Forecast Market Size for Robots as a Service (RaaS)



Source: Statista

The RaaS model offers several key advantages that make it an attractive option for businesses across various industries, these include: reduced capital expenditure, flexibility and scalability, ready to deploy solutions, and care-free maintenance and upgrades.

In addition to the operational advantages, RaaS also offers significant cost savings compared to traditional human labour.

For example, robots in a RaaS model are typically charged between $2 to $8 per hour, whereas the average hourly wage for a U.S. factory worker is approximately $28.19[6], according to the U.S. Bureau of Labor Statistics.

Moreover, the ability to rent robots as needed allows businesses to align their workforce more closely with production demands. During periods of high demand, companies can increase their use of robots to boost productivity, while scaling back during slower periods to reduce costs.

9. Upgradeability & Self-Maintenance

The rapid pace of advancements in artificial intelligence (AI) will dramatically reshape numerous industries, including robotics. While the rapid advancement brings incredible opportunities, it also raises concerns for potential buyers of AI-enabled robots. The concepts of over-the-air (OTA) upgrades and self-maintenance offer promising solutions.

Adoption of AI-enabled robots could be hindered by the fear that investment will quickly become outdated as newer, more advanced models are released. Fortunately, OTA updates offer an efficient solution to this problem, allowing robots to receive new features, enhancements, and improvements without the need for physical modifications.

[6] https://www.bls.gov/news.release/empsit.t24.htm

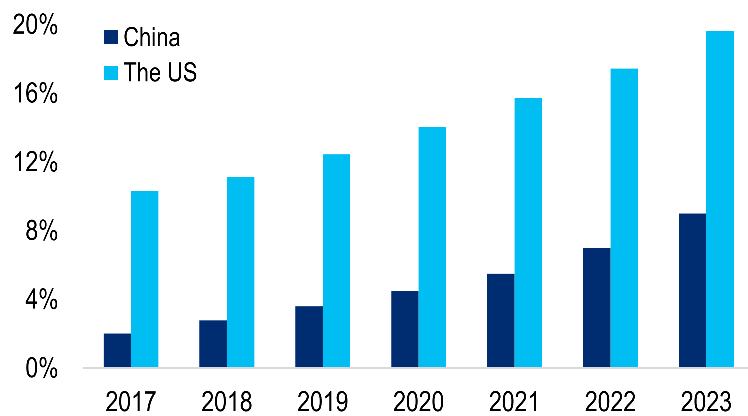
Cleaning & Maintenance

Domestic Cleaning Robots

Domestic cleaning is the most mature robotic market to date measured by units already installed and is a large potential market going forward.

The first commercially available robotic vacuum cleaner Trilobite was released in the 1990s. Later in 2002, iRobot, which has become the No.1 player in the robotic vacuum cleaning market, released the first robotic vacuum cleaner Roomba. By 2004, over 1 million Roombas had been sold.[7] Penetration is estimated at 20% in 2023[8,9] in more developed economies like the US and 12% in 2024 in developing economies like China[10]. And adoption is still expanding at a fast pace.

Figure 11. Robotic Vacuum Cleaner Penetration Rate (%)



Source: Citi Global Insights, Statista

What these robots do is simple – going around the house vacuuming and mopping the floor according to preset schedules and navigating back to their charging stations when batteries are running low or after the job is done.

Higher-end models can adjust their cleaning setting intelligently according to flooring types. Models like Roomba Combo® j7+, for example, can automatically retract its mop when it moves on top of a carpet.[11]

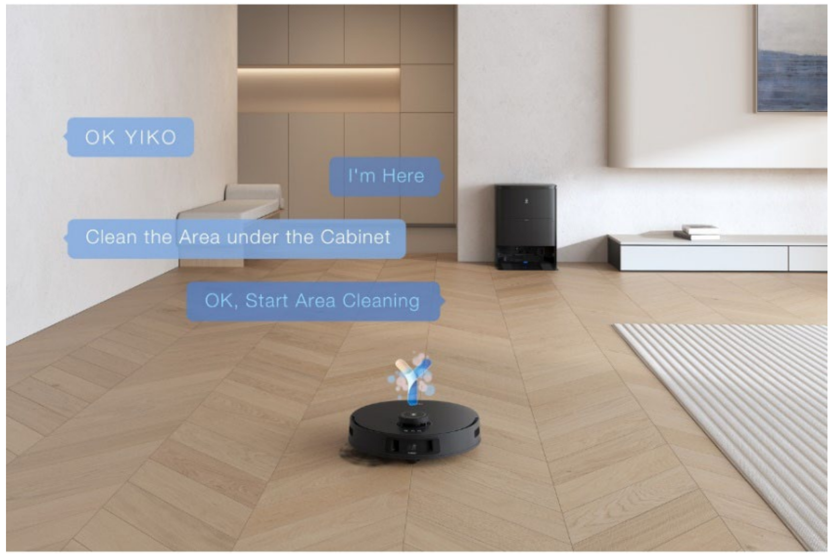
The AI Upgrade

AI is bringing a huge upgrade to the existing products on the market by making them smarter.

Some of the more advanced models are equipped with Large Language Models (LLMs) so that the robots can understand human language instructions from the users in and work in a more ad-hoc and customized way. For example, the latest premium model from Ecovacs DEEBOT X5 PRO OMNI is equipped with the AI Voice Assistant YIKO.

[7] iRobot's Roomba Robotic Floorvac Surpasses 1 Million In Sales (iRobot)
[8] Robotic vacuum cleaner installed base in the US (Statista)
[9] Number of households in the US (Statista)
[10] Penetration rate of robot vacuum cleaners in China (Statista)
[11] Roomba Combo® j7+ Robot Vacuum and Mop (iRobot)

Figure 12. Ecovacs YIKO AI Voice Assistant



Source: Ecovacs

What separates the higher end and lower end models is how they navigate around the environment without running into obstacles and getting stuck. Cheap and old models simply run the algorithm that instruct them to turn to another direction when running into obstacles.

Vision-only solutions used on many premium models use only cameras as the sensor. The same technology also underpins the FSD (Full Self-Driving) system on Tesla EVs, which uses Computer Vision (CV, a sub-branch of AI) to identify obstacles on the floor. The robot learns about what different obstacles look like, how to optimize the route and effortlessly navigate around non-flat areas.

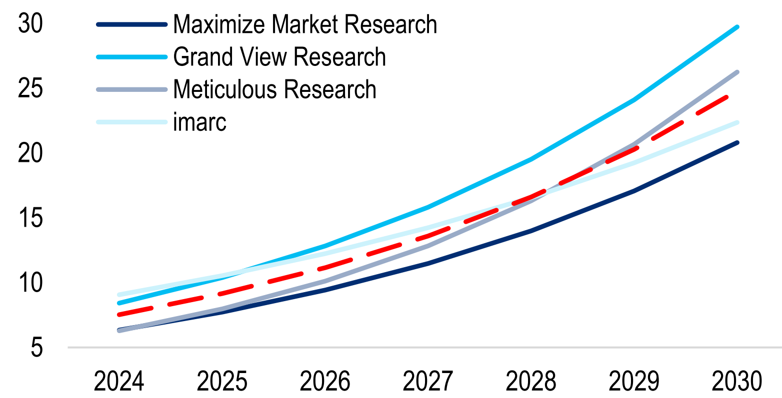
The accuracy and intelligence of vision-only solutions has caught up fast to alternatives thanks to rapid advancements in processors, algorithms and AI model designs. For example, iRobot's 2022 Genius Home Intelligence platform iRobot OS was able to recognize over 80 common objects by learning from a large dataset of more than 43 million objects in people's homes.[12]

Market Analysis

According to Euromonitor, the market size of robotic vacuum cleaners expanded at 13% 2018-23 CAGR from $3.8bn in 2018 to $7bn in 2023 globally.[13] The average of 4 independent sources indicates the market size for robotic vacuum cleaners is expected to grow to $24.8bn by 2030, up from $7.5bn in 2024, at a CAGR of 22%.

[12] iRobot Unveils iRobot OS (iRobot)
[13] Citi Research Report on the Global Robot Vacuum Market

Figure 13. Global Robotic Vacuum Cleaner Total Addressable Market (TAM) (in $bns)

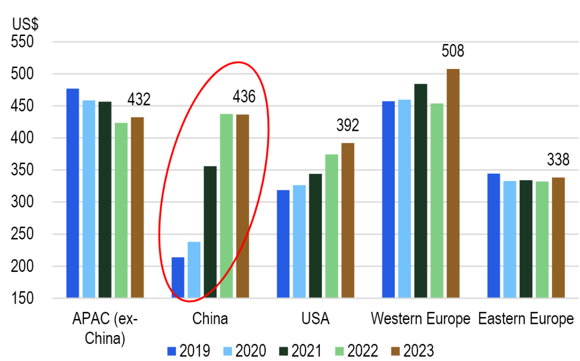


Source: See Chart, Citi Global Insights

According to Euromonitor, the Average Selling Price (ASP) is highest in Western Europe (2023: $508). In China, robotic vacuum cleaners have experienced very quick product upgrades in the past 5 years as industry players rapidly launched premium models with docking stations.

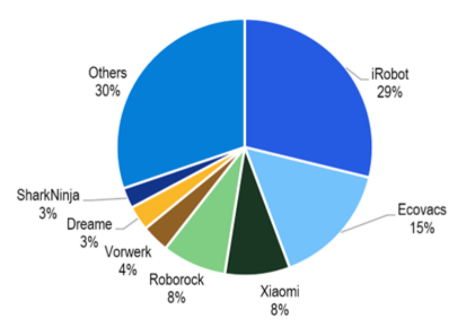
For the year 2024, the Asia Pacific region is expected to remain the largest market for robotic vacuum cleaners (34% of global market), followed by Western Europe (29%), USA (21%) and Eastern Europe (6%).[13]

Figure 14. Robotic Vacuum Cleaner ASP by Geography, 2019-23



Source: Euromonitor, Citi Research

Figure 15. Market Share of Robotic Vacuum Cleaner by Retail Sales Volume, 2023, Worldwide



Source: Euromonitor, Citi Research

Our Proprietary Analysis

According to our analysis, the global unit number of domestic cleaning robots is expected to grow from 286mn in 2024 to 793mn by 2035 (CAGR: 10%) and further to c.1.2bn by 2050 (CAGR: 3%).

We first extrapolate the number of households to 2050 by country (156 countries included) using the formula **Number of Households = Population / Average Size of Households**. The 156 countries are grouped into 3 regions by development phase according to the United Nations: more developed regions[14], less developed regions[15] and least developed regions[16].

World Population Analysis

According to UN Population Office, world population is forecast to grow 18.7% during the 26-yr period between 2024-50. This is considerably slower than 36.7% seen during the 26-yr period up until 2024 & 53.7% during 1972-98.

- The population in more developed regions should remain largely flat (since 2013). More demographically challenged countries, such as Japan, are looking at robots as a way to continue to grow GDP.
- The majority of population growth (c.70%) forecast during 1960-2050 is from less developed regions due to its large population base (c.⅔ of the world's population) and fast growth rate.
- Population is set to grow the fastest in least developed regions, but from a small base. During the 26-yr period from now through to 2050, less and least developed regions should each contribute half of the world's population growth.

Average Household Size Analysis

The more economically developed a region is, the smaller the average household.

- Household size has been trending slowly downwards in more developed regions since before the 1960s. In 1960, it was 2.9. In 2050, we assume the number to drop to 1.9.
- Household size only started to trend downwards in the 1990s in less developed regions but is decreasing at the fastest pace among all development groups. There were 4.8 people in an average household in 1992, but the number is estimated to drop to 3 by 2050.
- Household size started dropping at a slow pace in least developed regions in the early 2000s (5.4 average in 2000) and is forecast to reach 4.6 people by 2050.

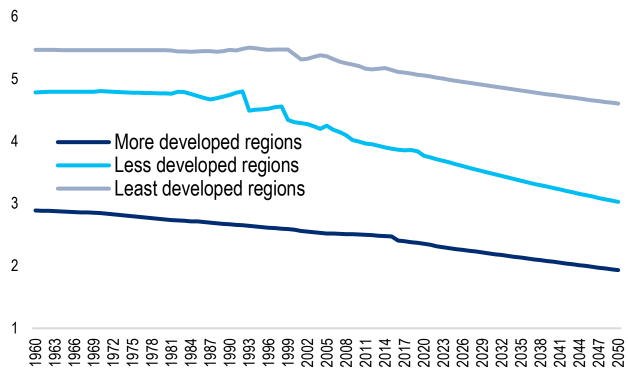
Household Number Analysis

- We estimate the more developed regions grow from 314mn households in 1960 to 659mn by 2050 (2.1x growth).
- Less developed regions are seeing significant growth in number of households due to both fast growth in population and sharp drop in average household size. From 385mn households in 1960, the forecast is growth to 2,127mn households by 2050 (5.5x growth). Less developed regions will account for c.⅔ of all the households in the world by 2050.

[14] More developed regions: Europe, Northern America, Australia/New Zealand and Japan.
[15] Less developed regions: Asia (except Japan), parts of Africa, Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia.
[16] Least developed regions: 46 countries, located in sub-Saharan Africa (32), Northern Africa and Western Asia (2), Central and Southern Asia (4), Eastern and South-Eastern Asia (4), Latin America and the Caribbean (1), and Oceania (3).

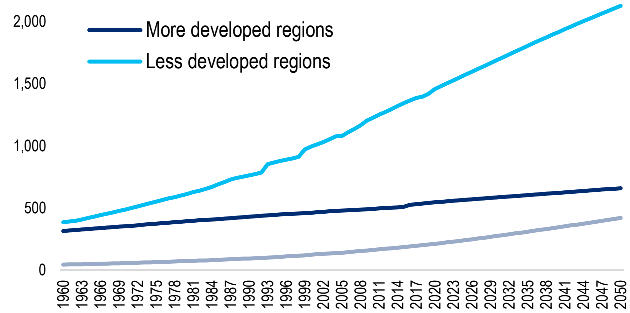
- For least developed regions, the number of households grow fastest albeit from a much smaller base. Least developed regions had 44mn households in 1960 and this is expected to reach 420mn households by 2050 (9.5x growth).

Figure 16. Size of Average Household by Development Group



Source: Citi Global Insights, CORESIDENCE

Figure 17. Number of Households by Development Group (in mns)



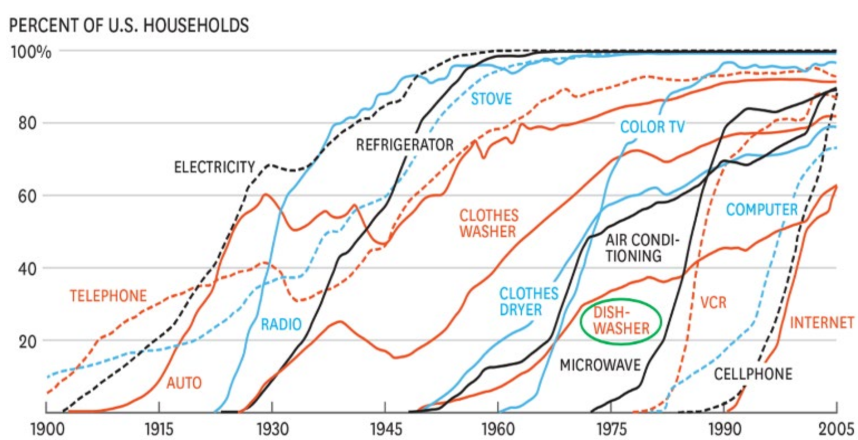
Source: Citi Global Insights

Penetration Analysis

We assume penetration rate of domestic cleaning robots in more/less/least developed regions will grow to around 50%/25%/12.5% by 2035 from 20%/9%/0% in 2023 - we assume that the developed world penetration resembles US and less developed world resembles China and then slow down to grow at a linear pace to 65%/32.5%/16.3% by 2050. We believe these estimates could prove conservative given:

- A new study from Roborock of 2,000 Americans examined people's attitudes toward chores and technology and revealed 73% of respondents think their homes would be cleaner if they had robots doing their chores.[17]

Figure 18. Robotic Vacuum Cleaner Could See Similar or Even Faster Adoption Trajectory vs Dishwasher



Source: Nicolas Felton, The New York Times, Citi Research

[17] [Seven in 10 people Would Totally Trust a Robot to do All of Their Chores (Yahoo News UK)]

- One comparable appliance for robotic vacuum cleaners in terms of adoption, according to Citi Research, is dishwashers.[13] According to latest data from US Energy Information Administration (EIA), 90mn out of 123.5mn or 73% of households have dishwasher installed at home in 2020.[18]
- Some multistory households may use two or more (one for each floor) robotic vacuum cleaners so that the actual average number of robotic vacuum cleaners per household could be more than the 1-to-1 ratio we use.

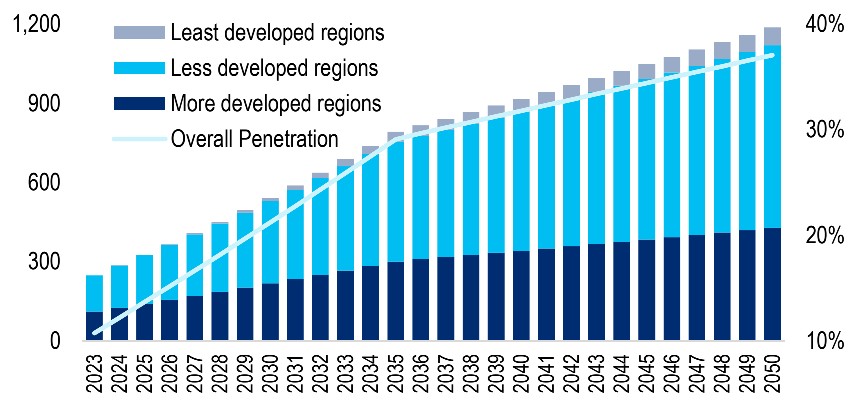
Total Unit Forecast

Finally, we use the formula **Unit Number = Penetration into Households * Number of Households** to calculate the unit number forecasts for different development regions.

Based on the above approach, we estimate there were 111mn/137mn domestic cleaning robots in more/less developed regions in 2023, which we forecast to grow to 300mn/454mn by 2035 at a CAGR of 8.7%/10.5% and then further to 428mn/691mn by 2050 at a CAGR of 2.4%/2.8%.

We estimate the total unit number worldwide to reach 794mn by 2035 (CAGR: 10%) and then further grow to 1.2bn by 2050 (CAGR: 3%). The overall penetration rate grows from 11% to 29% between 2023 and 2035 and then to 37% by 2050.

Figure 19. Total Unit Forecast for Domestic Cleaning Robot (in mns)



Source: Citi Global Insights

Commercial Cleaning / Maintenance Robots

We expect robots to be deployed at scale in commercial buildings given the estimated payback period vs. the salary of human janitors. Robots are already working in public spaces like offices, hospitals, schools and airports, and can be more efficient than humans.

For example, the R12 Rex Scrub from LionsBot (Figure 20) is a large area robotic floor scrubber for commercial use. The robot uses many sensors from Lidar (Light Sensor) to Cameras (Depth Sensor) for active obstacle tracking.

[18] 2020 RECS Survey Data (US Energy Information Administration)

Sweeper robot SweepXL from Fybots (Figure 21) is a fully autonomous robot with self-cleaning and self-garbage discharge. It uses in-house built intelligence, navigation, and self-positioning to ensure mobile and fixed obstacles are avoided.

Figure 20. R12 Rex Scrub from LionsBot

Source: LionsBot

Figure 21. Sweep XL from Fybots

Source: Fybots

Case Study: Ozmo from Skyline Robotics

Skyscraper window cleaning robot Ozmo from Skyline Robotics. Ozmo features a six-axis robotic arm with a brush attached to the end to do the cleaning.

Powered by AI, machine learning and computer vision, Ozmo makes most of the decisions on its own. It calculates 250 times per second to decide on how much pressure to apply to the windows, where to apply the brush, and when to move the scaffolding to the next level – all this to determine the most efficient and safe cleaning path.[19] It also takes stock of the building's facade conditions and reports back data on potential issues that need to be addressed.[19]

[19] Meet the AI-powered robots that could change the multibillion-dollar window-cleaning industry forever (Fortune)

Figure 22. Ozmo from Skyline Robotics

Source: Skyline Robotics

Window cleaning is a dangerous job, with a growing labour shortage. According to a study from online jobs resource Zippia, 75% of window cleaners nationally are above the age of 40, while just 9% are 20-30 years old.[20]

Ozmo cleans 3 times faster than traditional window cleaning[21] and is expected to lower on-site labor costs by 75%[19]. The current cost of the Ozmo is c.$500,000, with a 3-5-yr payback period.[22]

Ozmo is currently used in Tel Aviv and New York and has worked on major Manhattan buildings such as 10 Hudson Yards, 383 Madison, 825 3rd Avenue and 7 World Trade Center in partnership with the city's largest commercial window cleaner Platinum and real estate giant The Durst Organization.[22]

[20] Window Cleaner demographics and statistics in the US (Zippia)
[21] Skyline Robotics deploys Ozmo window cleaning robot in New York City (Robotics 24/7)
[22] Window-washing robots are working on Manhattan skyscrapers (CNBC)

Michael Brown
CEO
Skyline Robotics

What AI Robot solutions are you offering?

Skyline Robotics is focused on automating the window cleaning industry.

We are a deep tech and robotics and automation company disrupting the $40B window cleaning industry. The company believes that all work at heights (5m+) should be automated. Skyline knows that significant amounts of injuries occur at heights each year and that the dangerous, dull and dirty tasks that humans complete alone today, are ripe for automation. The company's vision includes a cooperative working model between robots and humans and that combining the best qualities of each, enables superior efficiencies in the variable environments our technology.

Skyline's Ozmo is the world's first robotic-armed window-cleaning robot that keeps skyscraper windows clean, increases worker safety and creates new jobs.

- Ozmo brings operational visibility
- Ozmo fills labor shortages by operational efficiencies
- Ozmo bridges real world danger with data and sensors
- Ozmo is the safest solution for cleaning windows at heights

What challenges do you see in the next 3-5 years?

The acceptance of AI in the automated workforce is promising as we see robots used in warehouses, delivery services and even transportation now. Ozmo, while autonomous, is still operated by humans using a computer on the rooftop. The end result is humans and robots working together with humans kept out of harm's way while robots do the cleaning.

Ozmo's deployment in NYC marks the beginning. Ozmo robots are slated for future deployments in London, while Skyline has also secured key patents from Japan and Singapore.

Our Proprietary Analysis

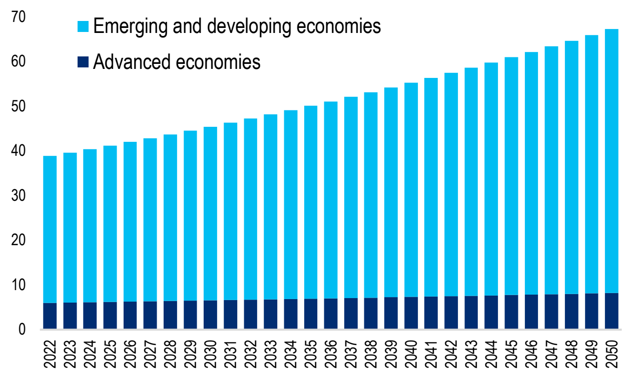
Our analysis forecasts the global unit number of commercial cleaning / maintenance robots will grow from an estimated 1.5mn in 2024 to 14.2mn by 2035 (CAGR: 23%) and further to 24.5mn by 2050 (CAGR: 3%).

According to International Energy Agency (IEA), there were 91bn/166bn m^2 of buildings in advanced / emerging and developing economies in 2023 and by 2030, the number is expected to grow to 99bn/192bn m^2. Global building area is expected to reach 124bn/292bn m^2 by 2050 for advanced /emerging and developing economies.

Advanced / emerging and developing economies were estimated to have 25bn/57bn m^2 of commercial building as of 2023. The number is set to reach 28.5bn/73.5bn m^2 by 2035 and will further grow to 34bn/100.6bn m^2 by 2050.

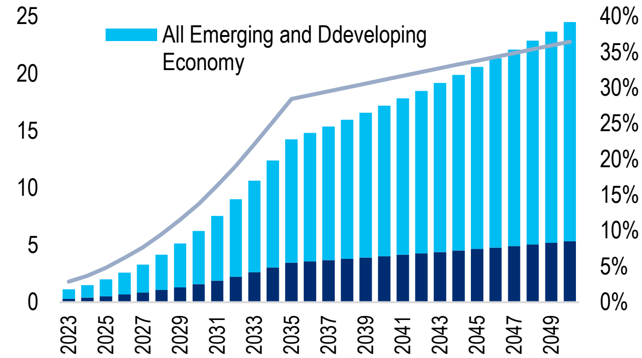
Using the data for total commercial building areas, we estimate the number of janitors employed in advanced / emerging and developing economies assuming janitor productivity stays roughly the same across advanced / emerging and developing economies respectively. We estimate there are 6mn/33.6mn janitors in advanced / emerging and developing economies in 2023. We forecast this will increase to 7mn/43mn by 2035 and will further grow to 8mn/59mn by 2050.

Figure 23. Global Number of Janitors by Development Group (in mns)



Source: US Bureau of Labor Statistics, iiMedia Research, Citi Global Insights

Figure 24. Total Unit Forecast for Commercial Cleaning / Maintenance Robot (in mns)



Source: Citi Global Insights

We assume penetration rate in advanced / emerging and developing economies will grow to 50%/25% by 2035 from 5%/2.5% (lower than that of domestic cleaning robots) in 2023 at a more exponential pace and then slow down to grow at a linear pace to 65%/32.5% by 2050 (to match that of domestic cleaning robots eventually given demand around the world and an attractive payback period).

Despite the obvious business case and rapid growth, we expect the unit number of commercial cleaning / maintenance robots to be much lower than domestic cleaning robots given the much larger number of households. There were 0.3mn/0.8mn domestic cleaning robots in advanced / emerging and developing economies in 2023. We forecast the number will rise to 3.5mn/11mn by 2035 at a CAGR of 23%/22% and then further to 5.3mn/19mn by 2050 at a CAGR of 2.9%/2.2%.

We estimate the total unit number worldwide will reach 14mn by 2035 (CAGR: 23%) and then further grow to 24.5mn by 2050 (CAGR: 3%). The overall penetration rate will increase from 3% to 28% between 2023 and 2035 and then to 36% by 2050.

Transportation

Autonomous Vehicles (AV)

We could write an entire Citi GPS report on AVs – indeed Citi has published 4 Car of the Future[23] reports over the last decade – but space in this report allows a few highlights before we explain our assumptions and conclusions to 2050.

Citi's first Car of the Future report in 2014[24] was early and AV development is a reminder that technological progress often goes slowly, then quickly. This is known as Amara's Law. Ford's Doug Field has noted that full driverless autonomy is "harder than putting a man on the moon, to create an L4 robotaxi that can operate in a dense urban environment.[25]" Add in safety testing for regulatory approval and it is not surprising that the pace of progress has appeared slow.

Much has however been happening under the hood. ADAS (Advanced Driver Assistance Systems) penetration has been rising, from emergency breaking, to adaptive cruise control, to lane departure or collision warnings. Vehicle Automation is classified in 5 stages, from no automation (0) to full self-driving with no driver assistance in any condition (stage 5).

Many cars have 1 or 2 automated features. Stage 3 allows autonomous driving with a human ready to take over as needed. Stage 4 is full automation, which can include no steering wheel or pedals, within certain boundaries.

Figure 25. Waymo Jaguar I-PACE

Source: Waymo

Figure 26. Baidu Apollo 3.0

Source: Shutterstock

For L3+, according to AVIA's 2024 report, AVs have already driven 70m miles on US public roads[26], up 59% from July 2023. Continuing Doug's moon analogy, this is the equivalent to 293 round trips to the moon.

Waymo, the AV company spun out of Google, has driven over 25m miles[27]. Post the landmark decision in August 2023 by the California Public Utilities Decision to allow Waymo to drive without human operators in San Francisco, the company is now delivering 100,000 rides per week[28]. This is a ten-fold increase from last year.

[23] Car of the Future v4.0 Update: The Race for the Future of Networked Mobility
[24] The Car of the Future: Transforming Mobility As We Know It
[25] Ford-VW driverless car venture folds in face of tech challenges
[26] AVIA - State of AV 2024
[27] Waymo Safety Impact
[28] Waymo is now providing more than 100,000 paid robotaxi rides per week in the U.S.

General Motor's AV division, Cruise, saw one of its cars involved in a well-publicised crash last year, but has resumed testing cars under the guidance of human supervisors, in Phoenix, Houston and Dallas[29]. Amazon's AV subsidiary Zoox received approval to drive on public roads in 2023 and is testing in Austin, Miami and Las Vegas[30]. Uber has partnerships with 14 AV companies[31].

AV development and testing is taking places in many other countries, including UK, Norway, Germany, UAE, Singapore, South Korea, Japan and Australia. The biggest experiments, momentum and market opportunity however can be found in China. 60 Chinese cities had issued AV road test licences by the end of 2023[32].

There are several important reasons why countries are driving towards an AV future, including:

1. Saving Lives – 1.4m lives are lost to traffic accidents each year[33]. Human error accounts for 90%[34] of these and technology can help. Robots have better vision and faster reaction times than humans. They do not get tired, sleepy, distracted, enraged or drunk. Waymo has reported a 70% reduction is crash rates versus human drivers.

2. Obeying Rules – NHTSA data shows 4.4m Americans jumped red lights in 2022[35], a cause of many deaths. AVs are designed to follow traffic rules better than humans. Updated rules, such as speed restrictions, can also be transmitted simultaneously to AV fleets.

3. Saving Money – NHTSA estimates the annual societal cost of traffic accidents is in the hundreds of billions of dollars[36]. Robotaxis promise cost saves from no human driver, as well as reduced cost of ownership versus a depreciating parked asset. AVs also reduce the costs of parking and could in time lower insurance premiums.

4. Saving Time – Americans spend one hour on average per day behind the wheel and collectively spend 5bn hours stuck in traffic per year[37]. Robotaxis can also save time and money parking.

5. Added Mobility – AVs can help those who cannot drive – the infirm, elderly, young, or the inebriated – or those concerned about who they are getting in a car with.

Despite these potential benefits and the momentum taking place, clearly many challenges remain.

- The technology to drive safely and consistently as high speeds in dynamic situations is complicated and expensive, but both should improve. For example, Baidu's latest robotaxi costs less than half its previous model at c.$28,500[38]. The

[29] Cruise resumes supervised autonomous driving with safety drivers
[30] Zoox - We're expanding testing to Austin and Miami; Zoox - Las Vegas, let's ride
[31] Uber - Driving autonomous forward
[32] 16,000 test licenses for autonomous vehicles issued in China
[33] https://waymo.com/about/
[34] https://www.nature.com/articles/s41467-024-48526-4
[35] https://www.ft.com/content/03a2e26c-d501-4686-8d15-c26b34f329ff
[36] NHTSA: Traffic Crashes Cost America $340 Billion in 2019.
[37] The Car of the Future: Transforming Mobility As We Know It
[38] Baidu launches robotaxi that costs less than half of earlier model

progress and cost reductions of multi-modal AI systems that enable AVs since our first Car of the Future report have been extraordinary.

- The risks require a very high standard of safety for regulatory approvals, a standard higher than that of human drivers. This has created a chicken and egg situation with more miles needed to create data, evidence and confidence. While more proof was needed to allow more AVs, it does appear a tipping point may have been reached given the quantity and pace of miles driven.
- The legal framework for liability and insurance of AVs takes time. There is also risk from failed software updates, data breaches or cyber-attacks. The prospect of a hacked AV being used as a weapon will remain a worry. Protectionism, market concentration concerns and resistance from unemployed drivers could also rise.

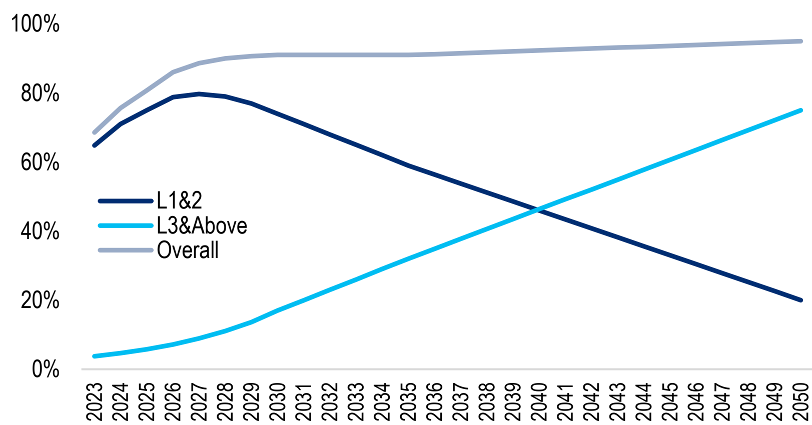
Our Proprietary Analysis

Using penetration numbers from Citi Research as a basis for starting number, we forecast global unit for Level 3 and above AV will rise from an estimated 27mn in 2024 to 380mn by 2035 (CAGR: 27%) and then to 1.9bn by 2050 (CAGR: 11%).

We extend AV penetration rates in new car production to 2050. We expect ADAS penetration into new cars to peak in 2027 when 80% of the new car manufactured will have some level of Autonomous Driving (AD) capabilities (L1 – L2), e.g., parking assistance, automatic emergence braking.

From 2027 onwards, more advanced autonomous driving (L3 – L5), where vehicles can perform all driving tasks and are responsible for monitoring the driving environment, is expected to take off.

Figure 27. AV Penetration into New Cars



Source: Citi GPS

Total Unit Forecast

We extrapolated new car production and total number of cars on the road data from 2035 to 2050 with a slower growth rate. New car production was growing at a 3.4%

CAGR before the pandemic[39], and we assume a 2.5% CAGR across 2035-50. From a 2.3% CAGR growth of total number of cars on the road pre-2035, we assumed the growth rate will gradually slow down to 0 during 2035-50.

Assuming a depreciation life of 13 years, we can calculate the total unit number for L3 – L5 AD with the formula **Total AD Number $_{t}$ = Total AD Number $_{t-1}$ + Annual AD Shipment $_{t}$ + Annual Upgrade to AD from ADAS $_{t}$ - Annual AD Shipment $_{t-13}$**. For L1 – L2 ADAS, the formula is **Total ADAS Number $_{t}$ = Total ADAS Number $_{t-1}$ + Annual ADAS Shipment $_{t}$ - Annual Upgrade to AD from ADAS $_{t}$ - Annual ADAS Shipment $_{t-13}$**.

We conclude that there will be 380mn/947mn cars with AD/ADAS capabilities by 2035 and the number will further grow to 1.9bn/128mn by 2050 at a CAGR of 17%/ -12% (ADAS taken over by AD gradually). 20%/50% of cars on the road will have AD/ADAS capabilities by 2035 and 82%/6% by 2050. The overall penetration will reach 70%/88% by 2035/2050.

Drones

Autonomous drones are already a large, growing and important market. One example of a company active in this space is Zipline. The company has flown 90m miles and made 1.25m commercial deliveries around the world, including emergency blood, vaccines or medical supplies. It also delivers food and consumer products, flying up to 140 miles in a trip and determining locations down to one centimeter. The company claims delivery speeds are 10x faster than those from traditional cars, with lower cost, less noise and zero emissions. Given the critical nature of some of their deliveries, the FAA allows Zipline to deliver beyond the line of sight of observers.

Alternatively visit the Drone World Congress which this year hosted over 500 drone companies and 10,000 attendees. The largest on display at the 2024 event can carry 400kg and travel 4500km. Others can transport people. Or enter their drone racing competitions. But be warned that autonomous systems can already race faster than human world champions. These systems also brought a swarm of 8,100 drones together for a new world record display over Shenzhen.

[39] Estimated worldwide motor vehicle production from 2000 to 2023

Figure 28. Examples of Enterprise Drones Use Cases

Source: Citi GPS

Our Proprietary Analysis

The global unit number of drones is expected to grow from an estimated 37.1mn in 2024 according to data from Levitate Capital to 73.4mn by 2035 (CAGR: 6.4%) and further to 149.4mn by 2050 (CAGR: 5%).

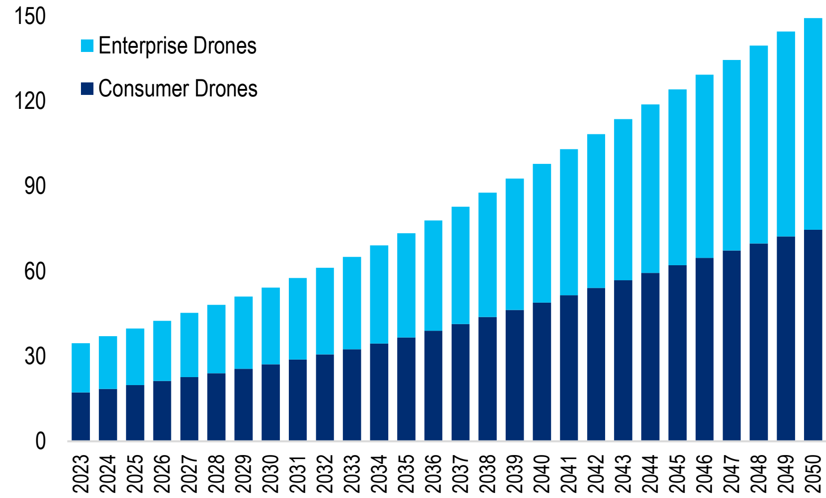
According to Levitate Capital[40], the consumer drone market is forecast to grow from $4.2bn in 2025 to $5.3bn by 2030, while the enterprise drone market is estimated to grow from $16bn in 2025 to $29bn by 2030 in a base case scenario. While projected units are similar for consumer and enterprise drones, the higher price points for enterprise leads to a 5.5x higher TAM by 2030.

Extending our own analysis to 2050 we make four primary assumptions. The first is this 50/50 unit split between consumer and enterprise drones continues. Secondly, we assume a 6% CAGR in unit growth from 12.4m drones shipped in 2023 to 26mn by 2035. Thirdly we then slow the annual shipment growth rate for consumer/enterprise drones down to match long-run GDP growth of 3.1% by 2050. Finally, we assume a depreciation life of 3 years for drones.

We can calculate the total unit number with the formula $\textbf{Total Unit Number}_{t} = \textbf{Total Unit Number}_{t-1} + \textbf{Annual Shipment}_{t} - \textbf{Annual Shipment}_{t-3}$. We conclude that number of consumer/enterprise drones will grow to 36.7mn/ 36.7mn by 2035 from 17.3mn/17.3mn in 2023 (CAGR: 6%) and the number will further grow to 74.7mn/74.7mn by 2050 at a CAGR of 5%. The total unit number is forecast to reach 73.4mn by 2035 and then further grow to 149.4mn by 2050.

[40] https://levitatecap.com/levitate/wp-content/uploads/2020/12/White-Paper-v4.pdf

Figure 29. Total Unit Forecast for Drones



Source: Citi GPS

Note we have not extended the analysis to drone use cases in the military, law enforcement or use in safety areas such as firefighting. This suggests the total drones in use over this period could be higher. These areas are however discussed in Chapter 8 of this report.

Humanoids

Humanoids – a robot that resembles a human in shape – are no longer confined to sci-fi. There are tremendous advances being made in this field of robotics and as we highlight below humanoids will become a very large new market opportunity.

All of the areas of technological progress discussed in Chapter 1 underpin the changes happening in humanoids but it is the combination of improvements in AI and dexterity that are the most dramatic. Multi-modal AI allows humanoids to see, to move, to communicate with humans, to learn, to understand tasks and action them. Agibot from Yuanzheng, for example, claims to already be able to thread a needle.

We count over 50 types of humanoids being developed around the world. They have a growing collection of capabilities. The Unitree H1 can move at 3.3m/s and can dance[41]; should you want a robot that can do backflips and parkour, Atlas from Boston Dynamics can; Phoenix's Gen 7 can learn complex tasks in under 24 hours[42]; and Unitree's G1 humanoid can fold itself up to fit into a cupboard[43].

Figure 30. Optimus Gen 2 – Tesla

Source: Tesla

Figure 31. H1 Evolution V.30 - Unitree

Source: Unitree

The capability of humanoids will continue to advance, partly as the addressable market size could be among the biggest in the world – labor's share of GDP is over 50% of global GDP and over 60% in North America[44]. The combination of growing intelligence and growing dexterity means that humanoids could substitute for an increasing number of jobs. As shown in the table below, if Elon Musk's prediction of a $25,000 ($20-30k) price point for Telsa's Optimus is correct, a 36-week payback period is possible using the lowest US minimum wages of $7.25. Minimum wages in California ($16), average factory wages ($28) and average US nurse wages ($41) are added to highlight other payback scenarios. The conclusion in each is clear, that humanoids could be very compelling economically.

[41] https://www.unitree.com/h1
[42] https://www.msn.com/en-us/news/other/sanctuary-ai
[43] https://www.unitree.com/g1
[44] https://ourworldindata.org/grapher/labor-share-of-gdp?tab=chart

Figure 32. Humanoid Payback Period Sensitivity Table (in weeks)

Hourly Wage ($/h) \ Humanoid Price ($)	15,000	20,000	25,000	30,000
7.25	21.6	28.7	35.9	43.1
16	9.8	13.0	16.3	19.5
28	5.6	7.4	9.3	11.2
41	3.8	5.1	6.4	7.6

Source: Citi GPS

The argument for humanoids is not just economic. Some jobs are dangerous or undesirable for humans and are better suited for robots. In other cases, labour shortages exist and can fill these roles. Robots also don't leave or take holidays.

Ben Reed
Chief Marketing Officer
Sanctuary AI

What AI Robot solutions are you offering?

Sanctuary AI builds humanoid robots and the AI-enabled control systems that power them. The goal is to make machines that understand and act in the same way people do, in order to do work. Our category-leading Phoenix™ general purpose robots are smart enough, capable enough, and dexterous enough to do work just like a person. We are building this technology to help address growing labor challenges. In the U.S. alone, September labor data shows approximately 8.2 million job openings, but only 7.2 million unemployed workers. We're currently focused on applications in industries where there are significant job vacancies such as automotive, manufacturing, and logistics. Growing market need and the accelerating pace of AI development is forecasted to propel humanoids to a multi-billion dollar market in the next decade. Developments in AI over the past year have allowed humanoid robots to learn tasks more quickly, with Sanctuary seeing a reduction in new task automation time from weeks to less than 24 hours.

What challenges do you see in the next 3-5 years?

There are two things that will unlock general purpose humanoid robots: human-like, dexterous hands and an AI control system which can manipulate them. Hand dexterity and fine manipulation **enable more than 98 percent of all work**, and powerful AI control systems are key to equip robots to interact with and manipulate objects in unstructured or dynamic environments. To create these AI systems, we need data. But while LLMs can learn from text on the internet, it is not as simple to collect the high quality, high fidelity training data needed. This data collection stage is where most humanoid robotics companies are currently focused.

Companies in the space will also be focused on the path to mass manufacturing. Manufacturing and deploying AI humanoids at scale allows the collection of the data needed to train the AI systems which control the robots. Over the next 3-5 years, you should expect significant refinements to the design and build costs of general purpose AI humanoids, which will be a key indicator of market readiness.

A big part of the thesis for humanoids is simple – we have engineered our man-made world to work for humans so humanoids can fit straight in without significant infrastructure changes.

We see and analyze seven main use cases for humanoids. Due to economic and environmental factors the first use case area will be in the industrial sector, including manufacturing and warehouses. These offer more contained areas for robots to operate and suffer from unfilled positions in the US. Robots can be usefully employed in lifting, transporting, loading, assembly, inventory restocking, or checking for defects.

A second similar use case is in construction where robots can carry, lay bricks, or paint. The construction workforce worldwide is significant, but the challenge of navigating around obstacles on sites limits our initial adoption estimates.

In retail humanoids can help with shelf stacking, customer service (such as locating items), or cleaning. Humanoids can help with last mile delivery bottlenecks, navigating paths, stairs, knocking on doors, or opening delivery boxes.

In hospitality, robots are already active in China delivering items to hotels rooms. Humanoids could pick this up and extend to welcoming or assisting in hospitality, for example the Kime humanoid below used in bar tending.

Figure 33. KIME - Macco Robotics

Source: Macco Robotics

Figure 34. EVE – IX Technologies

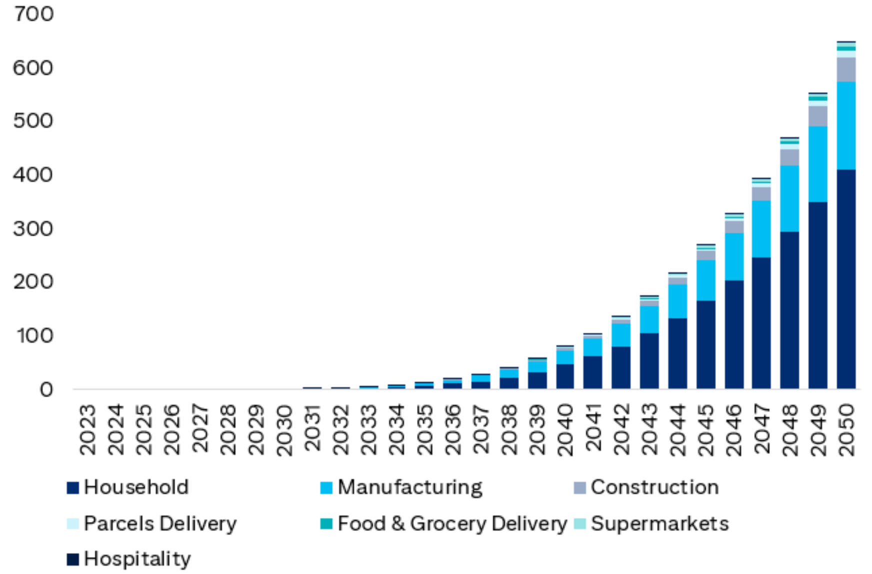
Source: 1X Technologies

One of the biggest opportunities is improving care for the elderly or infirm. This is covered in more detail in the care section of this report. Aging populations and a shortage of care / social workers will aid demand. Humanoid care workers could also allow people to stay in their homes for longer, with help 24/7/365, reducing dependency on relatives or carers who move on.

While humanoids can augment care in hospitals and care-homes we see the majority of demand coming from the elderly in their homes. Another primary use case for humanoids in households is help with cleaning: hoovering; using a dishwasher; tidying; with laundry.

Across these seven use cases we estimate humanoids could total 13.3m worldwide by 2035, growing to 648m by 2050.

Figure 35. Humanoid Unit Number Forecast by Type



Source: Citi GPS

We see the first significant use cases in industrials. We forecast households will become the largest unit market by 2050. While other use cases could be compelling, such has delivery in hotels or shelf stacking in hotels, these markets are dwarfed in unit size by households and industrials.

Figure 36. Humanoid Analysis Breakdown by Use Case (in mn units)

Use Case	2035	2050	CAGR
Home Services	7.9	411.2	30%
Industrials	4.6	164.2	27%
Construction	0.4	44.4	37%
Parcel Delivery	0.0	13.3	48%
Food & Grocery Delivery	0.0	6.9	44%
Supermarkets	0.2	6.4	25%
Hospitality	0.0	0.8	22%
Total	**13.2**	**647.2**	**30%**

Source: Citi GPS

In each use case we estimate the size of the total market for three regions (developed, less developed, least developed) to cover most of the world, then use different penetration rates for each use case and each region. We analyzed the number of households, supermarkets, and hotel rooms through 2050. We also analyzed the number of people estimated to be working in industrials, construction and delivery.

It is not clear what the augmentation versus substitute rates could be. For example, each tractor did not directly substitute for one worker or horse. Indeed, the most powerful tractor today, Big Bud 747, has 760 horsepower[45]. Alternatively, could a

[45] https://www.williamsbigbud.com/.

robot operating 23 hours a day (Telsa's aim) do the work of three human workers (i.e. a 1-3 ratio). Clearly this will be situation dependent, but for simplicity's sake we have assumed a 1-1 demand ratio in our analysis for now.

We have made assumptions on starting periods based on supply, economics and environments. End penetrations rates vary. We have analyzed 30% / 20% / 10% rates in 2050 for industrials for Developed / Less / Least regions.

In households we have factored in 22% / 11% / 5%. This takes account of populations aged over 80, but many under 80 may benefit from support.

Figure 37. Breakdown by Development Group (in mn units)

Development Group	2035	2050	CAGR
More developed regions	7.9	179.5	23%
Less developed regions	5.3	433.9	34%
Least developed regions	0.0	33.8	63%
Total	**13.2**	**647.2**	**30%**

Source: Citi GPS

While adoption is likely higher initially in developed regions given wage economics, our estimates conclude that less developed regions will account for two-thirds of the humanoid market by 2050 given the size of their populations and labor markets.

For more details on our humanoid analysis, please see our humanoid deck recently published.

Dr Harry Kloor
Founder and CEO
Beyond Imagination

What AI Robot solutions are you offering?

We are focusing on robots for specialized, highly skilled roles, starting with bio-manufacturing. These high-paying jobs require intense and specialized training, require high precision, and are physically demanding due to the need for work to be done in containment facilities.

Our advanced AI Brain architecture incorporates numerous different AI modules, working in concert like the lobes of the human brain. This allows our robots to process complex data, make informed decisions and learn new tasks with minimal human intervention. Designed to learn similarly to humans — through observation, repetition and continuous refinement – the AI brain also enables robots to share knowledge seamlessly across the entire fleet. Furthermore, the AI brain was built from the ground up to be completely auditable, transparent and safe to work alongside humans.

The cost savings and productivity gains that can be unlocked by AI humanoid robots capable of performing a wide range of complex tasks represent a compelling proposition, and we expect a TAM in the trillions. If one robot can do the work of three to four humans and can work any time, day or night, this will enable massive increases in productivity.

What challenges do you see in the next 3-5 years?

The greatest challenge for AI robots is demonstrating the ability to safely perform a wide range of real-world tasks across diverse and dynamic environments. While simulations and controlled demonstrations highlight the potential of AI powered humanoids, their behavior outside these settings can be unpredictable and, in some cases, unsafe.

No company has yet demonstrated the deployment of humanoid robots in real-world environments. No one has demonstrated actual cost savings from the use of humanoid robots in factories. And no one has come close to demonstrating fully autonomous robot behavior.

Through the targeting of specific verticals, and our engineering team's dedication to challenging industry assumptions, we are confident that we will begin to deploy pilot robots in the near term.

While 648m humanoids by 2050 is significant, one prediction we have come across sees 10 billion by 2040[46]. Why the difference? In addition to the 12 general robot challenges covered in Chapter 10 later in this report, we see a number of reasons why the humanoid market will take time to build:

1. Humanoids are so new that the most advanced are only in prototype, pilot or initial production phases. The highest number we can find so far is Yuanzheng looking to produce 100 units per month in November 2024[47]. Tesla has suggested commercial production of its Optimus robot in Tesla factories in 2025 and for purchase by external customers by 2026[48].Figure AI is looking to start production in 2025 with in 2025 with a few hundred humanoids. Production is more advanced in China than the rest of the world, but estimates are for just 10,000 units in 2026. It will take time for units to ramp.

2. Given point 1, humanoid capability is unproven, and the history of technology is developments at the start of the S-curve often take time, especially for hardware. For example, while UBTech has already deployed humanoids in auto production lines, the CEO notes they are operating at 20% of human efficiency levels[49]. This is expected to reach 100% in the next 1-2 years and then surpass human levels given they can work more hours. It is of course possible this timeline stretches.

3. Humanoid costs are high and will need to fall to encourage mass adoption. The average price globally is $86,000 according to China's Blue Book. Unitree's G1 is the cheapest model we are aware of on the market today, priced at RMB 100,000 ($14.3k), a sixth of their previous H1 model ($90k). If, as Elon Musk has suggested, Telsa's Optimus can be priced at $20-30k the payback periods versus human labour could be significantly shortened. Prices however still need to be competitive versus other non-humanoid robots.

4. The versatility advantage of humanoids could be a disadvantage if more specialized robots outperform in certain tasks, such as hoovering or

[46] https://www.diamandis.com/blog/10-billion-humanoid-robots-life-on-mars
[47] https://www.sohu.com/a/801928918_114877
[48] https://www.theguardian.com/technology/article/2024/jul/23/elon-musk-tesla-humanoid-robots-optimus
[49] http://www.china.org.cn/china/Off_the_Wire/2024-08/24/content_117385824.htm

manufacturing. The Swiss army knife is not the knife of choice for butchers. Humanoids generalized capability could mean there is not one killer app initially. Also, compared to say EV's bought to replacing existing cars, forming an entirely new market is harder. When doing so redesigning production lines to use other robots may prove to be more efficient or economic than slotting in humanoids. The horse was not replaced by an electric horse design.

5. Costs will come down over time, but the industry is so new there is no specialized supply chain currently. Most companies appear to be building their own parts, often with the use of 3D printing. Default rates should improve over time but could limit production near term. Costs and defects will fall as the supply chain improves, but scale economies also require more sales and thus time.

6. The economics of humanoids includes maintenance costs and replacement periods. Beyond Imagination estimates a replacement rate of 7 years. This compares with an average life of 8 years for a vacuum cleaner[50], 12 years for an EV[51] and 3 years for an iPhone[52]. It is too early to be certain about the total cost of ownership.

7. Development, production and maintenance will also depend on talent. In the Citi GPS Unleashing AI report last year we highlighted a significant talent shortage in AI given 4.7 job postings for each professional. The same is likely for humanoids given how nascent this market is versus the growth opportunity.

8. Many of the factors above depend on capital to finance R&D, production and talent. As highlighted in Chapter 9, capital has started to flow into humanoids but it is still very early stage.

9. We suspect supportive policy will have a part to play. Just as the EV market has seen much faster adoption in Norway (80% penetration)[53], or China (22%) than the US (6%), subsidies, regulations and coordinated ecosystems matter. Rising protectionist and security concerns could impact the market as well.

These factors influence the timing and magnitude of our forecasts, but we still conclude the technological possibilities, use cases and economics will mean the nascent humanoid market will eventually become very large (we estimate 648m units by 2050). With expected price declines going forward we estimate the Total Addressable Market for humanoids can reach $209bn by 2035 and $7trn by 2050.

[50] https://www.idealhome.co.uk/house-manual/cleaning/how-long-should-vacuum-cleaners-last
[51] https://www.caranddriver.com/features/a31875141/electric-car-battery-life/
[52] https://www.iphonelife.com/content/how-long-do-iphone-last-how-to-know-when-to-upgrade-your-iphone
[53] https://www.wri.org/insights/countries-adopting-electric-vehicles-fastest

Industrial

In the future, fewer and fewer factory workers will be busy forklifting products and parts around — this can be done more efficiently and effortlessly by specialized robots called Automated Mobile Robots (AMRs). Unlike their predecessors Automated Guided Vehicles (AGVs), which can only follow predetermined routes, and often require operator oversight, AMRs are more intelligent and can navigate the factory floor independently.

The secret behind AMR's intelligence is Simultaneous Localization and Mapping (SLAM). SLAM technology enables each robot to explore its unknown yet everchanging environment by continuously mapping the area while keeping track of its own location via a real-time information feed. Current industrial solutions focus on visual SLAM, in which the robots are equipped with advanced cameras and AI processors to enable vision and automated decision-making (e.g., route planning and collision avoidance).

The most recent manufacturing labour storage in the US stood at 505,000 in July 2024, c. 3.8% of overall employment in the sector.[54] Material handling remains a significant part of labour expenses, accounting for 20%-50% of total operating costs in factories.[55] Looking forward, according to Deloitte and the Manufacturing Institute, the US manufacturing industry could see a net need for as many as 3.8 million jobs between 2024 and 2033.[56] Without significant changes, more than 5 in 10 or 1.9 million of these jobs could go unfilled if workforce challenges are not addressed through 2033.[56] Leaving this gap unfilled would cost the US economy $1 trillion by 2030.[57]

With the cost of robots dropping rapidly at the same time, AMR solutions are attracting attention from manufacturers struggling finding quality workers. According to Interact Analysis, prices for some mobile robot types will drop by as much as 60% between 2021 and 2027 owing to increased competition mainly from China, and also due to economies of scale as production increases.[58]

We are still in an early stage for AMR deployment in smart factories — commercial deliveries at-scale only started in 2021, when AMRs surpassed AGVs in revenues for the first time.[59]

More than 4 million industrial robots operated around the world in 2023 according to IFR, representing a 12.4% CAGR during 2013-23.[60] Top 5 countries (China, Japan, the US, Rep. of Korea & Germany) accounted for 79% of 2023 global industrial robot shipments in total with China alone accounting for 51%. Despite reshoring trends, China's share dominance is expected to continue going forward.

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[54] Job Openings Levels and Rates (US Bureau of Labor Statistics)

[55] The Effect of Material Handling Strategies on Time and Labour Fatigue in Window Manufacturing (IAARC)

[56] US Manufacturing Could Need as Many as 3.8 Million New Employees by 2033 (Deloitte)

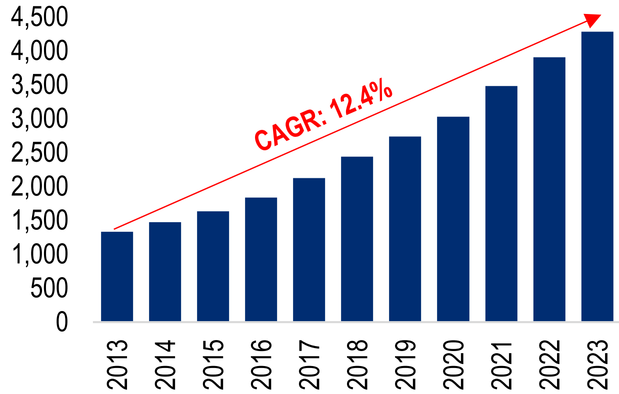
[57] Creating pathways for tomorrow's workforce today (Deloitte)

[58] The Mobile Robot (Interact Analysis)

[59] 100,000 Mobile Robots Shipped In 2021 (Interact Analysis)

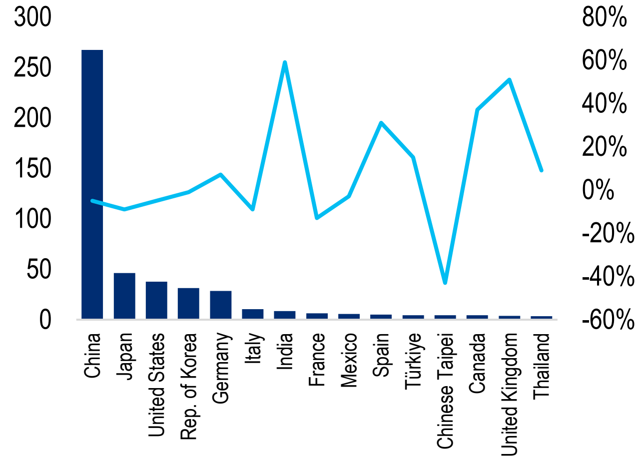
[60] World Robotics 2024 (International Federation of Robotics)

Figure 38. Global Installation Base of Industrial Robots 2023 ('000 of units)



Source: World Robotics 2024

Figure 39. Annual Installations of Industrial Robots 2023 ('000 of units)



Source: World Robotics 2024

OTTO Motors is an example of an AMR-as-a-Service solutions provider for factories. In one megafactory occupying 1 million square feet where 100% of the transportation is done through an AMR fleet, 1,100 total miles are travelled with 5,200 tasks completed every day.[61]

According to OTTO, the potential cost saving is high when deployed at scale. The standard OTTO 100 model (1:1 human capacity) works 24/7/52 for an annual cost of $15-25k per vehicle (c. $2.3 / hour), while the larger OTTO 1500 model (4:3 human capacity) costs $40-50k per vehicle annually (c. $3.9 / hour). The cost of OTTO AMRs is 10% of that of a labor equivalent, 20% that of a forklift driver equivalent, 50% of that of a conveyor system equivalent and 66% of a AGV system equivalent. As a result, the payback period is very favorable – less than 1 year for system lease and between 1-2 years for vehicle-only lease.[61]

AI and Robots: Cyclical headwinds rather than AI adoption have been the recent market driver

For light industrial storage and retrieval robots like AMRs and AGVs, there have been two very distinct (and offsetting) market trends since the pandemic. As in many applications, the capabilities and developments of AI have leapt forward, but the automation and robotics end-market itself has remained very challenged. The light AS/RS (storage and retrieval) market peaked in 2022, as low interest rates and high eCommerce penetration spurred adoption. This pulled forward a lot of investment, which then retreated as interest rates increased and eCommerce penetration (temporarily) reversed. US warehouse construction expenditure is now down ~20% YoY, and E-Commerce as % of total retail sales has only just now, in mid-2024, retraced back to the highs seen as the start of the pandemic.

[61] The business case for autonomous mobile robots (AMRs) in manufacturing (OTTO Motors)

Lowering costs are the near-term focus

Near-term anticipated applications focus on massively reduced set up times for industrial facilities (including coding), efficiency identification in design, and in service. Low-code and no-code applications, including using LLM to program robots and other intelligent automation devices, are already being put in place in 2024. Our trip earlier this year to the Hannover Trade Fair, an industrial automation event, saw multiple applications of AI focused on set-up efficiencies for automation using AI, particularly in using LLM models.

Many automation companies point to the potential for customers to increase EBIT by 20% or more through AI led efficiencies in automation set-up.

We can already see applications interpreting natural language instruction for industrial robots, although there remains an API between the AI software and the robot control software. Such applications have already been applied in some instances for optimizing warehouse automation.

While cost reduction through set up times is the most common case for now, new cases are clearly emerging. We expect these to gather pace over time.

- AI pattern recognition is a key requirement in monitoring robots (or drones). Use cases include detecting methane leaks in pipelines, electrical faults in transmission grids, or fractures in structures.
- AI route optimization in logistics applications.
- AI led simulation in product and process design, using scenarios a human may not even think of.
- Further development on the concept of "Digital Twins", with realistic real time digital renderings of physical products and processes and to allow natural language interaction.

Our Proprietary Analysis

Using data from Interact Analysis and Statista as a basis for starting number, the global unit number of AGV & AMR running on factory floors or in warehouses is expected to grow from 2.4mn in 2024 to 28.3mn by 2035 (CAGR: 25%) and further to 181.4mn by 2050 (CAGR: 10%).

According to Interact Analysis, Automated Guided Vehicles (AGV) covered > ½ of annual shipment of moving robots on factory floors or in warehouses in 2019. But AGV have gradually been in decline facing the competition from the more intelligent AMR since the start of the pandemic. By 2035, AMR will account for 91% of all AMR & AGV shipments, while AGV accounts for 9%.

We further assume that this annual shipment ratio stays roughly flat between 2035-50 and the growth rate of AGV annual shipment decreases gradually to global long-run GDP growth rate (3.1%) by 2050.

Assuming a depreciation life of 10 years for AGV/AMR, we can calculate the total unit number with the formula **Total Unit Number** $_t$ **= Total Unit Number** $_{t-1}$ **+ Annual Shipment** $_t$ **- Annual Shipment** $_{t-10}$.

There were 0.6mn/1.1mn AGV/AMR in 2023, and the number will grow to 4mn/24.3mn by 2035 at a CAGR of 16%/28% and then further to 16.5mn/165mn by 2035 at a CAGR of 7%/10%.

Service Robots

Hospitality Robots

Robots are already working in the service sector including accommodation, catering, entertainment, retailing and more. Restaurants and hotels are among the most significant use cases.

In restaurants, robots can work as waiters/waitresses, welcoming and seating customers, taking orders, serving food, or clearing tables after the meal.

In hotels, robots can help human employees with multiple tasks including cleaning, getting the room ready for the next guests, carrying luggage to rooms and delivering food orders or various other room services to rooms.

BellaBot Case Study

Pudu Robotics, a Chinese robot provider specializing in service robots, has shipped over 80,000 units to customers. Their robots are adopted in various industries like restaurants, retail stores, hotels, hospitals, factories and schools.

Their robot Bella is 1.3m in height, weighs 55kg and moves at a speed of 0.2-1.2m/s.[62] Bella has a max load of 40kg and can work for over 10 hours on a single charge (or one can simply replace the battery to make it work 24/7).[62] Bella is retailed in China at a price point of CNY 62,000 ($8,600).

Bella is already trialed in large restaurant and hotel chains in China. One example is Haidilao, top 5 catering brand in China and No.1 in hot pot category with over 1,300 stores covering 164 cities and over 100 overseas stores. The smart Haidilao restaurants in Beijing and Shanghai require zero human intervention to operate.

Bella can lead customers to their seat and can understand natural language instructions to serve food to specific tables. The smart weight sensor on their tray makes sure customers take the right dishes every time. They will stop by if they see customers waving at them. Their latest 3D-vision obstacle avoidance technology makes sure they never bump into customers during operations.

Temi V3 Case Study

Temi offers Robot as a Service (RaaS) solutions. Temi V3 is their latest autonomous personal AI assistant robot (with Alexa built in). Temi V3 is 1m tall, weighs 12kg and moves at a speed of 1m/s. It can operate up to 8 hours upon a single charge and will update its own software when needed over the air.[63]

The built-in AI system allows temi V3 to self-learn its surroundings and understand where it is, what it's seeing and where it's going.[63] Temi V3 can navigate by itself with an accuracy of 5cm or follow humans.

The robot can be used in various scenarios. The moving video call function makes it a perfect fit for telehealth. In offices, temi V3 can deliver coffee or food to desks or meeting rooms. In restaurants, temi V3 can welcome people into the restaurant as a host and server as it seats customers and takes their orders using either voice or its touchscreen.

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[62] Pudu Robotics
[63] Temi Robot

Felix Zhang
Founder and CEO
Pudu Robotics

What AI Robot solutions are you offering?

Pudu Robotics specializes in developing advanced service robots tailored to various industries, with a focus on addressing labor shortages, enhancing customer experience, and optimizing operational efficiency. Our product range includes:

Commercial Delivery Robots (e.g., BellaBot, KettyBot): Widely used in F&B, retail, and hospitality for food delivery, customer greeting, and marketing engagement.

Commercial Cleaning Robots: Multi-functional robots designed for sweeping, scrubbing, vacuuming, and mopping.

Industrial Delivery Robots: Ideal for factories and warehouses, streamlining material transport and logistics operations.

By leveraging advanced AI technologies—such as large language models (LLM), computer vision, machine learning, sensor fusion, deep learning, and topological navigation—we make our robots intuitive, precise, and efficient. These innovations have accelerated the commercialization and widespread deployment of our robots, significantly boosting productivity and reliability.

The global commercial service robot sector is projected to reach USD 84.8 billion by 2028, growing at a CAGR of 15.4% from 2023 to 2028, according to Markets and Markets.

What main changes and challenges do you see in the next 3-5 years

In the next 3-5 years, advancements in AI algorithms, sensor technology, and battery efficiency will enable robots to perform complex tasks with greater autonomy and precision. These improvements will also lead to more diverse robot forms, including semi-humanoid and humanoid robots that interact naturally with humans and handle a broader range of tasks. Pudu Robotics is actively investing in these areas.

Lowering component costs and achieving economies of scale will make advanced robots more affordable, boosting adoption across industries. Enhanced IoT connectivity will improve real-time data processing and operational efficiency.

However, as robots integrate more into daily operations and handle sensitive information, robust cybersecurity and data privacy measures will be crucial. Additionally, public perception, regulatory compliance, and workforce reskilling will be vital to ensure smooth integration and widespread acceptance. By addressing these challenges, the AI robotics sector is set to enhance efficiency, productivity, and quality of life across industries.

Our Proprietary Analysis

We examined the opportunity to use humanoids in the hospitality sector in a recent report. Looking at the wider global opportunity for robotic waiters / waitresses through 2050, such as those above, our analysis led to forecasts of 9.6mn by 2035 and 15mn by 2050 (CAGR: 3%).

Based on data from sample countries, we assume that waiter/waitress employment makes up 0.8%/1.2%/0.4% of the population in more/less/least developed regions.

Although there have been many trials of robot waiter/waitress serving food and drinks at restaurants or bars in the US, the UK, Japan and China (e.g., Bella, Skylark), at-scale deployment of food service robots has yet to take off.

Given the capability of robots to carry to and from tables is already high, we believe it is just a question of time and economics before these trials turn into deployments. While robots may not be deemed appropriate for higher end restaurants, they are likely to be more cultural accepted over time if they speed up or improve service in other dining segments. We assume that the penetration rate in more/less/least developed regions will grow to 20%/10%/3% by 2035 from close to 0 in 2023 at a more exponential pace and then slow down to grow at a linear pace to 30%/15%/5% by 2050.

We use the formula **Unit Number = Penetration into Waiters/Waitresses * Number of Waiters/Waitresses** to calculate the unit number forecasts for different development regions.

We conclude that there will be 2mn/7.3mn hospitality robots in more/less developed regions by 2035 and the number will further grow to 3mn/11.6mn by 2050 at a CAGR of 2.7%/3.1%. We forecast that the total unit number worldwide will reach 9.6mn by 2035 and then further grow to 15mn by 2050 (CAGR: 3%). The overall penetration rate will increase from close to 0 to 11% between 2023 and 2035 and then to 16% by 2050.

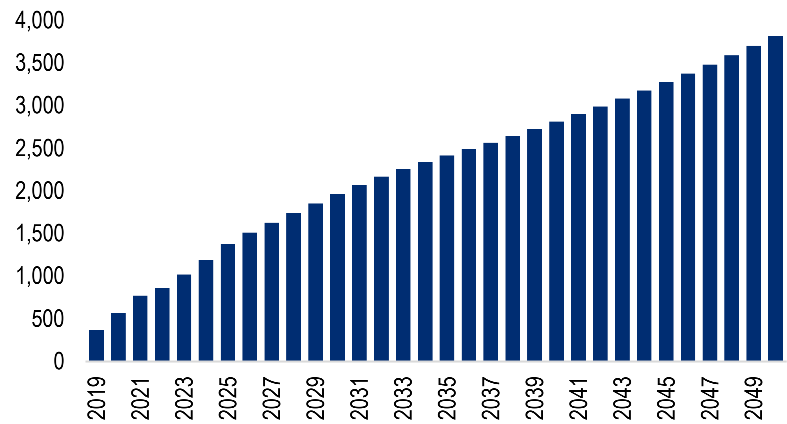
Delivery Robots

Food & Grocery Delivery

The global online delivery market (including meals and groceries) was valued at $367.5bn in 2019 and is expected to reach $1,853bn by 2029 at a CAGR of 18%.[64] We expect the market to continue growing to $3,818.5bn by 2050 (assuming annual growth rate gradually slows down to 3.1% = global long-run GDP growth rate according to IMF) at a CAGR of 4%.

[64] Online Food Delivery - Worldwide (Statista)

Figure 40. Global Food Delivery Market Size (in $bn)



Source: Statista, Citi Global Insights

Robots are expected to assist human food & grocery delivery drivers/riders in the future including picking up orders, ensuring timely deliveries through route optimization, finding addresses and communication with customers.

Starship Technologies Case Study

Starship delivery robots have completed over 6mn deliveries with thousands of delivery robots operating across over 60 locations around the world.[65] The robot is able to deliver groceries, food takeaways and packages.

Starship Technologies is growing fast – it took the company 78 months to achieve the first million-delivery benchmark and only 7.5 months on average to achieve the next 5 million-deliveries. The company plans to expand to 50 college campuses in the US.

Each robot is equipped with 12 cameras to see the surrounding environment to ensure accurate and safe navigation and can travel at c.4mph – similar to a fast pedestrian walking speed. It can also carry up to three bags of groceries.[65]

In the UK, each food delivery costs £0.99-2.99 depending on the weight of the item[65], and parcel deliveries cost £7.99/month for an unlimited number of deliveries.[66]

Parcel Delivery

The top 5 countries (China, US, Japan, India, Germany) account for 88% of global parcel delivery in 2022. Global daily parcel volume is experiencing significant growth post the pandemic during mainly driven by the growth in developing regions.

According to Effigy Consulting, developed regions contribute to less than a quarter of the global total parcel volume in 2022, dropping from c.60% in 2015. Assuming that the growth trend gradually slows down (with parcel volume growth rate in developed regions decreasing more quickly than that in developing regions), the developed region share of parcel volume is forecast to drop to only 5% by 2035.

[65] Starship Technologies
[66] Starship Package Deliveries

We expect the growth rate in daily parcel volume for both developed and developing regions to gradually slow down after the rebound post the pandemic and eventually match long-run real GDP growth rates from 2035 onwards (1.7% for developed regions and 3.9% for developing regions according to IMF).

Figure 41. Starship Technologies Robot

Source: Starship Technologies

Figure 42. Manna Drone

Source: Manna Drone Delivery

Manna provides Unmanned Aerial Vehicle (UAV) last-mile delivery service to transport packages, medicines, foods, postal mails and other light goods. The company offers drone delivery service in Dublin and Dallas-Fort Worth, Texas now.[67] It was doing 200-300 deliveries per day in Dublin in June with plans to roll it out across the capital and to other places this year.[68]

Our Proprietary Analysis

Our analysis of food and grocery robots forecasts the market can grow from thousands in 2024 to 11.2mn by 2035 and further to 19.1mn by 2050 (CAGR: 4%).

We assume that only 50% of the growth in number of on-demand delivery orders will translate into the growth in the number of drivers/riders (the other half is expected to come from growth in their productivity & capacity).

The number of food & grocery delivery drivers/riders globally is estimated to grow relatively fast before 2030, but growth should gradually slow down thereafter. There were 15.6mn food & grocery drivers/riders in the world in 2019 and we estimate the number to grow to 58.7mn by 2050 at a CAGR of 4.4%. Developing regions will be the main growth driver for food & grocery delivery couriers.

Although there have been many trials in different places (e.g., Starship, Kiwibot), they are still very early in deployment and penetration. Penetration rates should grow faster for indoor food delivery robots (e.g., deliver coffee or food to desks or meeting rooms) than outdoor food delivery robots as it's easier to navigate inside apartment blocks or commercial buildings (e.g., offices and hotels) than outside.

For indoor delivery, we assume that the penetration rate in developed/developing economies will grow to 20%/13.3% by 2035 and then slow down to grow at a linear pace to 30%/20% by 2050. For outdoor delivery, we assume the penetration rate in

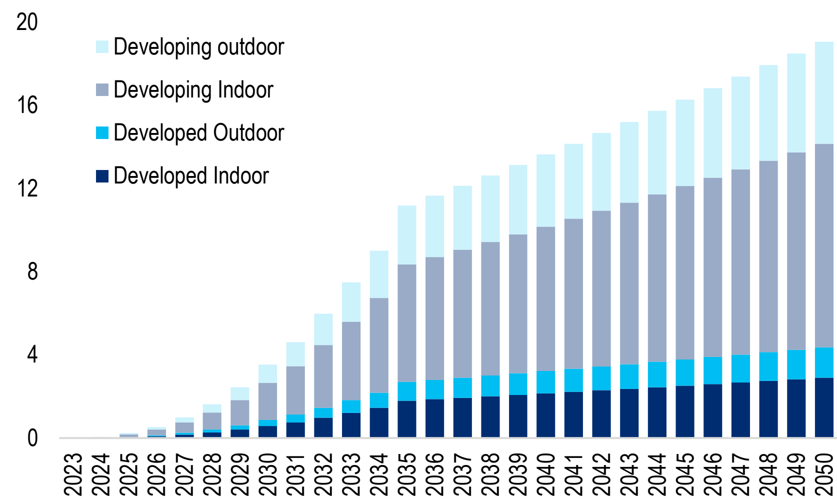
[67] Manna Drone Delivery
[68] Drone deliveries pass ice-cream test with flying colours in Dublin trial (The Irish Times)

developed/developing economies will grow to 10%/6.7% by 2035 and then to 15%/10% by 2050 following a similar pattern to that of indoor delivery.

Finally, we use the formula **Unit Number = Penetration for Indoor/Outdoor Delivery * Number of Food Delivery Couriers** to calculate the unit number forecasts for different development regions.

For indoor delivery, we conclude that there will be 1.8mn/5.7mn robots in developed/developing economies by 2035 and the number will further grow to 2.9mn/9.8mn by 2050 at a CAGR of 3.3%/3.7%. For outdoor delivery, we conclude that there will be 0.9mn/2.8mn robots in developed/developing economies by 2035 and the number will further grow to 1.5mn/4.9mn by 2050 at a CAGR of 3.3%/3.7%. The total unit number worldwide will reach 11.2mn by 2035 and then further grow to 19.1mn by 2050 (CAGR: 4%), as shown below.

Figure 43. Total Unit Forecast for Robotic Food & Grocery Delivery (in mns)



Source: Citi Global Insights

We analyzed use cases for parcel delivery in our humanoid analysis published in this recent report.

Healthcare

Care robots are robots primarily designed to assist human caregivers in providing care to the sick, elderly, or disabled. The combination of an aging population, caregiver shortages and rising healthcare costs offers a significant opportunity for care robots to offer support to both care givers and receivers.

By 2050, 1 in 6 people globally will be over 65, 1 in 4 for people living in Europe and Northern America[69] and by 2080, the number of people above 65 will outnumber children under 18[70]. With an aging population, there is an increased demand for care however there are not enough human carers. In the UK, Skills for Care reported a vacancy rate of 9.9% in adult care in 2022[71] – this translates to approximately 152,000 unfilled positions. In America, there will only be 3 potential caregivers for each person over 80 that needs care compared to 8 in 2010[72]. This shortage places pressure on existing caregivers, often leading to burnout and turnover rates 36% higher than other job roles[73].

Rising healthcare costs are also pushing for more efficient solutions. Global spending on health reached $9.8 trillion in 2021[74], with long-term care being one of the most expensive components. There is pressure to find cost effective ways to deliver care without compromising quality. Robots present an opportunity to fill these gaps by taking on routine tasks, alleviating some of the strain on existing healthcare providers.

Figure 44. The Giraff robot

Source: TelepresenceRobots

Figure 45. Nursing Care Robot

Source: Riken

Care robots can be used in various roles

The main potential use cases for moving AI-robots in healthcare include:

- **Remote monitoring:** Telepresence robots solve for patients who may not have access to regular in person care. They allow healthcare professionals to monitor and check in on patients remotely by performing tasks such as facilitate video calls, record vital signs, deliver medication reminders.

[69] https://population.un.org/wpp/Publications/Files/WPP2019_10KeyFindings.pdf
[70] https://reliefweb.int/report/world/world-population-prospects-2024-summary-results
[71] Skills for care, adult social care workforce data, 2022/23
[72] AARP, 2013
[73] Skills for care, adult social care workforce data, 2022/23
[74] WHO, Global healthcare spending trends

The Giraff robot enables doctors and family members to visit and interact through a screen and camera mounted on a mobile robotic platform. It is primarily intended to support elderly people who live alone with features such as a blood pressure station, timed pill dispenser and a pressure sensitive mat that can monitor vital signs during sleep or rest[75].

- **Assistive care:** Some elderly individuals may require daily support with activities such as moving around or getting dressed. Physical assistance robots for lifting and transferring patients can help reduce the physical strain on human caregivers while enhancing safety for both the patient and the caregiver.
- **Companionship:** Loneliness is a prominent issue for the elderly. 43% of Americans over 60 say they are lonely, and a study shows loneliness is as bad for your health as smoking[76]. The Citi Global Insights AgeTech report dives deeper into solving the issue of combatting loneliness with AI and companionship robots. Examples of companionship robots include those that are designed to interact with users through conversation or assist with memory recall activities to keep the elderly mentally active and engaged.
- **Delivery robots:** Robots can be used for specialised care related tasks such as medicine delivery and or material distribution. For example, the ZENA RX robot securely delivers pharmacy, laboratory and other clinical materials.

Trials are currently underway

The EU's flagship research programme, Horizon, contributes €1.3 billion to a public-private partnership exploring artificial intelligence, data and robotics, as well as supporting discrete projects related to robotics in care[77]. Between 2015 and 2020, the EU allocated €85 million to the 'Robotics for Ageing Well' initiative that aims to integrate robotic solutions into elderly care settings to reduce burden on human caregivers[78]. Similarly, the UK government invested £34 million in 2019 for robots that support elderly patients as part of their strategy to revolutionize adult social care[79]. Japan's Ministry of Economy Trade and Industry (METI) spearheaded the Robotics Care Equipment Development and Introduction Project under which successful robots such as Paro were designed.

Despite this investment, adoption remains limited for several key reasons:

- **Cost:** These robots are expensive. While government subsidies help, the cost of purchasing, maintaining, and training staff to use these machines is still a large limiting factor.
- **Increased workload:** The robots often require setup, supervision, and maintenance, negating their intended benefit of reducing the strain on human caregivers.

[75] https://telepresencerobots.com/robots/giraff-telepresence
[76] Loneliness and social isolation as risk factors for mortality
[77] https://www.socialeurope.eu/robots-in-social-care-the-human-touch-at-risk.
[78] https://www.technologyreview.com/2023/01/09/1065135/japan-automating-eldercare-robots/
[79] https://www.telegraph.co.uk/global-health.

- **Cultural resistance:** Many elderly people and caregivers remain resistant to the idea of robots taking over intimate tasks, preferring human interaction. Additionally, prolonged reliance on robots for emotional support may diminish meaningful human contact.
- **Technological limitations:** Current models, despite their sophistication, lack the versatility to perform all the necessary caregiving functions and often fall short in some areas especially in terms of emotional support.
- **Data privacy:** Robust privacy protocol is essential to protect patient data from cybersecurity breaches, especially in home environments.

Case study: Japan

Japan has been at the forefront of developing and adopting robotic solutions for eldercare given Japan has the oldest population in the world with 1 in 10 people over 80 years old[80]; almost 35% of its population is forecast to be over 65 by 2040[81]; there is a severe shortage of caregivers, projected to be a 570,000 shortfall by 2040[82].

Japan has invested in robots such as Paro (a therapeutic seal for dementia patients) and Pepper, a social humanoid robot able to recognize faces and perform basic human interactions and engagement.[83]

Figure 46. Pepper – Social Humanoid Robot

Source: Aldebaran

The Japanese government has encouraged the integration of these technologies into care facilities through initiatives such as the Robotics Care Equipment Development and Introduction Project, even offering subsidies to incentivise adoption. Despite this, adoption rates remain surprisingly low, with only 10% of

[80] https://www.weforum.org/agenda/2023/09/elderly-oldest-population-world-japan/
[81] National Institute of Population and Social Security Research https://www.bbc.co.uk/
[82] https://www.asahi.com/ajw/articles/15346218.
[83] https://www.aldebaran.com/en/pepper

eldercare institutions reporting using any kind of robot[84] and they often are left in the cupboard[85].

Interestingly, despite Japan associating with robots in pop culture, the use of robots in eldercare has faced resistance. The human aspect of caregiving rooted in Japanese culture often directly clashes with the mechanical, impersonal nature of robots.

Although many elderly individuals expressed curiosity about robots, there is a clear preference for human caregivers when it comes to intimate, emotional tasks. This is due to concerns that robots lack the emotional depth and empathy needed for meaningful care. The idea of robots providing personal care could also be a barrier to adoption.

Potential for AI care robots

As technologies evolve, we expect care robots to become more intelligent, adaptive, and autonomous. Care robots hold vast potential to revolutionise personalised healthcare, enhance emotional support and seamlessly integrate into smart home environments. We see robots potentially using machine learning to predict patient needs, adjust care plans and respond to emergencies.

Our Proprietary Analysis

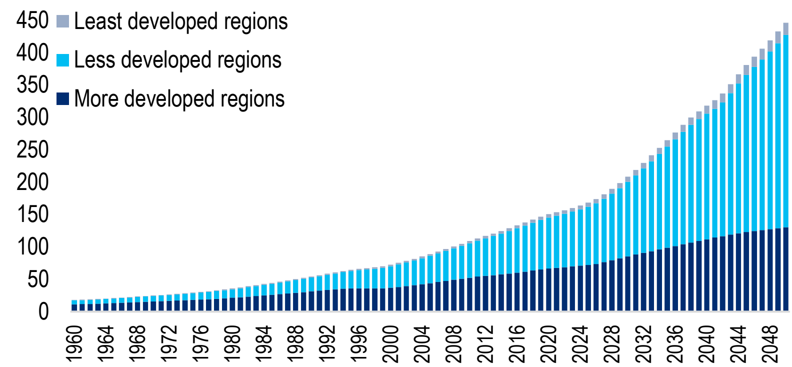
According to our proprietary demand analysis, the global unit number of caring robots is expected to grow from close to 0 in 2024 to 18mn by 2035 and further to 71mn by 2050 (CAGR: 7%).

We start by a regional analysis of the elderly population (>80 years). The world's population is aging fast. Almost 5% of the world's population will be aged over 80 by 2050 vs. only 0.6% in 1960 (7.7x growth). In total, 446mn people will be aged over 80 by 2050.[86]

- More developed regions have the most aged society. The elderly population has grown from 11m in 1960 (1% of total population), to 71mn today now and is forecast by the UN Population Office to grow to 131mn by 2050 (5.5% of total population & 12x larger than 90 years ago).
- Less developed regions are also aging rapidly. Elderly population in these regions is forecast by the UN Population Office to grow by over 3.4x between now (87mn) through to 2050. There will be 297mn people >80 years old in less developed regions by 2050 (4.6% of total population & 50x larger than 90 years ago).

[84] https://www.technologyreview.com/2023/01/09/1065135/japan-automating-eldercare-robots/
[85] https://www.cornellpress.cornell.edu/robots-wont-save-japan-eldercare-reality-care-robots-james-wright-09-12-2023/
[86] UN Population Estimate

Figure 47. Elderly Population (>80 years old) by Development Group (in mn)



Source: Citi Global Insights, United Nation

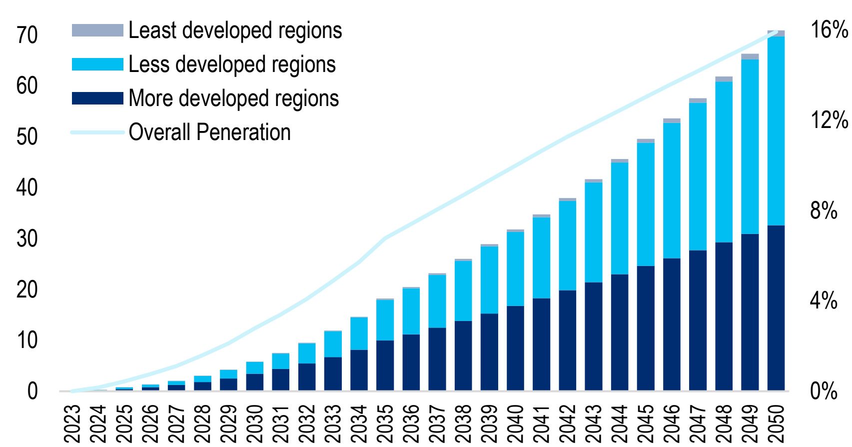
Various studies[87,88,89] suggest that roughly 7 in 10 elderly would be willing or indifferent to have some of their daily activities attended to by robots.

We therefore assume that penetration rate in more/less/least developed regions will grow to 10% (1/7 of 70%) / 5% (half that of more developed regions) / 2.5% (half that of less developed regions) by 2035 from 0 in 2023 and then grow linearly at a slower pace to reach 25%/12.5%/6.25% by 2050.

We use the formula **Unit Number = Penetration into Elderly Population * Number of Elderly Population** to calculate the unit number for caring robots forecast for different development regions.

Based on the above inputs, we estimate that there will be 8mn/10mn caring robots in more/less developed regions by 2035 and the number will further grow to 32.6mn/37mn by 2050 at a CAGR of 6%/8%.

Figure 48. Total Unit Forecast for Caring Robot (in mns)



Source: Citi Global Insights

[87] OLDER ADULTS' PREFERENCES FOR AND ACCEPTANCE OF ROBOT ASSISTANCE FOR EVERYDAY LIVING TASKS (NIH)
[88] Majority of elderly Irish people would favour 'care robots' to look after them, study finds (Irish Examiner)
[89] When do individuals choose care robots over a human caregiver? Insights from a laboratory experiment on choices under uncertainty (Elsevier)

Safety, Security & Military

As robotics technology continues to evolve, some of the most impactful applications will likely be in areas linked to safety, security & military, where robots are increasingly being deployed to perform tasks that may be too difficult or dangerous for humans.

Safety Robots

Safety robots represent a crucial application, particularly in environments where human lives are at risk. These robots are typically designed to operate in hazardous scenarios, where they can investigate or de-escalate dangerous situations while keeping human operators out of harm's way. By performing tasks such as inspections, safety robots play a vital role in ensuring the safety of workers.

A well-known safety robot is Spot, developed by Boston Dynamics. Spot is a quadruped robot designed for mobility across various terrains, making it ideal for inspections in energized, radioactive, or otherwise hazardous environments.

Figure 49. Boston Dynamics - Spot

Source: Boston Dynamics

For example, Spot can be deployed in nuclear facilities to inspect reactors and other critical components without exposing workers to radiation. Similarly, it can be used in chemical plants to detect leaks or other hazards, reducing the risk of exposure to toxic substances.

Another particularly interesting safety-related application of robots is in firefighting, where they can assist in battling blazes, and conducting search and rescue operations in hazardous conditions. Firefighters are often exposed to life-threatening situations such as extreme heat, collapsing structures and toxic smoke. Safety robots are beginning to transform this high-risk profession.

For example, thermite RS3 firefighting robot has been deployed in various fire emergencies.[90] It can operate remotely from a safe distance, keeping human firefighters out of dangerous environments.

[90] LAFD Debuts the RS3: First Robotic Firefighting Vehicle in the United States

Other specialized robots are designed to detect specific types of hazards. For example, the Taurob Gasfinder is developed to detect hazardous gases.

Figure 50. Taurob – Gasfinder

Source: Taurob

Security Robots

Security robots could become increasingly common in both public and private spaces. These robots are designed to perform tasks such as inspecting properties, predicting safety threats. In the UK alone, there are estimated to be around 150,000 security guards.[91]

One example of a security robot is the Knightscope K5, an autonomous security robot designed for both indoor and outdoor use. The K5 is equipped with features such as 360-degree video streaming and recording in high definition, thermal anomaly detection, and advanced AI for threat analysis.

The K5's ability to operate independently allows it to provide round-the-clock surveillance, making it an effective deterrent against crime in environments such as shopping malls and parking lots. Its thermal anomaly detection capabilities also enable it to identify potential fire hazards or unauthorized personnel, ensuring that security teams can respond promptly to any incidents.

https://lafd.org/news/lafd-debuts-rs3-first-robotic-firefighting-vehicle-united-states

[91] Estimated number of security guards in the United Kingdom from 4th quarter 2021 to 1st quarter 2024 https://www.statista.com/statistics/785269/security-guards-in-the-uk/

William Santana Li
Chairman and CEO
Kinghtscope Inc

Knightscope, Inc. (NASDAQ: KSCP) builds technologies to improve public safety, and our long-term ambition is to make the United States of America the safest country in the world. Our Autonomous Security Robots (ASR) that are patrolling across the U.S. are a combination of autonomy, robotics, AI and EV technology to help provide officers and guards unprecedented situational awareness to better protect the places that people live, work, study and visit. Additionally, the ASRs provide a physical deterrence that can help mitigate negative behavior before it starts. We believe long-term there is an opportunity to build a company that would be analogous to a defense contractor but instead is focused on the U.S. Dept of Justice, U.S. Dept of Homeland Security, the 19,000 law enforcement agencies and 8,000 private security firms with a wide array of cutting edge technologies.

Our technology has now operated in the field for over 3 million hours across the country, 24/7/365, fully autonomously (not remote control) through numerous winters and summers since 2015. Our focus now is optimization and scaling up operations.

One major challenge over the next 3 to 5 years is the tension in telecommunications costs and data transfer capabilities versus the need for compute at the edge. Long-term a significant number of robots will be operating in areas without the advantages of industrial strength Wi-Fi. The cellular network is just too costly and slow to transfer all the data to the cloud to be processed. So, there is a scramble now to shrink the compute and power needs so the computational work can be done in the field and not in the cloud - which is unfortunate.

For environments where terrain is a significant factor, the Ascento Guard is designed to offer a versatile solution. This autonomous, all-terrain security robot is designed to detect and communicate with intruders, monitor perimeter integrity, and manage parking, among other tasks.

Figure 51. Ascento Guard

Source: Ascento

Military Robots

Robots enhance the capabilities of military forces while reducing the risk to human soldiers in dangerous or hostile environments. Military robots are designed to perform a wide range of tasks, from transportation and logistics to reconnaissance, search and rescue, and even direct combat.

Drones

Drones, also known as unmanned aerial vehicles (UAVs), are aircraft without an onboard pilot, controlled remotely from the ground. These versatile devices are used in a variety of applications, including aerial photography, goods delivery, and military operations. With advancements in AI, drones can now fly in coordinated swarms, enhancing their operational capabilities across different environments.

Combat drones, such as the MQ-1 Predator developed by General Atomics, are seen as a key asset in modern military operations. These unmanned combat aerial vehicles are used for intelligence gathering, surveillance, target acquisition, and reconnaissance.

Figure 52. General Atomics - MQ-1 Predator

Source: Lt. Col. Leslie Pratt - afrc.af.mil

The MQ-1 Predator, for example, is equipped with various aircraft ordnance, including missiles and anti-tank guided missiles, allowing it to engage targets effectively while keeping human pilots out of harm's way. The use of such drones has transformed military strategy by providing persistent surveillance and precision strikes. Furthermore, while military drones are thought of to be relatively large vehicles (>8m in the case of the MQ-1 Predator), increasingly we are seeing miniaturized drones being used for military purposes.

The advanced capabilities, low cost, and ease of accessibility of consumer grade drones, especially the First Person View (FPV) drones used for racing, have become of increasing importance.[92] One example, produced by Shield AI, is a compact drone (<30cm long) that weighs only 1.5kg and is able to use AI to help map its environment.[93]

Surveillance and Reconnaissance Robots

Other military robots provide valuable intelligence while keeping human operators at a safe distance. The PackBot 525, for example, is designed to be a versatile robot designed for bomb disposal, surveillance, and reconnaissance missions. Capable of

[92] How drone combat in Ukraine is changing warfare https://www.reuters.com/graphics/UKRAINE-CRISIS/DRONES/dwpkeyjwkpm/

[93] Shield AI: Nova 2 https://www.epequip.com/wp-content/uploads/2022/07/Shield-AI-Nova-2_Brochure_EPE_Branded.pdf

lifting up to 44 pounds (20 kg), the PackBot 525 can be equipped with various sensors and cameras to perform tasks such as inspecting suspicious objects, detecting chemical or biological hazards, and gathering real-time intelligence in hostile environments. These robots can be deployed in urban environments, remote areas, and even inside buildings.

Figure 53. Teledyne Flir – PackBot 525

Source: Teledyne Flir Defense

Armed Robots

A particularly striking example of military robotics is the development of armed robots, such as the quadrupedal robot dogs demonstrated by China's military. These robots are equipped with automatic rifles mounted on their backs and can operate autonomously for two to four hours.

Figure 54. Robodog

Source: YouTube / CCTV Video News Agency

The deployment of such robots represents a significant advancement in combat capabilities, allowing for remote-controlled or autonomous operations in conflict zones. The use of armed robots raises important ethical and legal questions, particularly regarding the rules of engagement and the potential for unintended consequences in combat situations. However, from a military perspective, these robots offer a significant advantage by enabling forces to engage in combat while minimizing the risk to human soldiers.

Conclusion

The safety and security industry encompasses a wide range of sectors, including defense contracting, cybersecurity, physical security, and law enforcement. These sectors play a critical role in maintaining national sovereignty, public safety, and protecting private entities. They also come with big budgets. For example, global military expenditure in 2020 reached almost $2 trillion.[94]

Globally, these sectors employ millions of individuals, spanning various roles. For instance, globally, there are approximately 28 million active military personnel, including full-time soldiers and officers across different branches of defense forces.[95] The United States alone employs around 500,000 active-duty personnel.[96] Similarly, in the United States, there are roughly 1.2 million full-time law enforcement personnel as of 2018, according to the Bureau of Justice Statistics,[97] and millions more globally – around 10 million according to data collated on Wikipedia.[98] Furthermore, the private security industry employs 20 million globally.[99] Consequently, the possibility of augmenting such a workforce with robots, even if only by 5-10%, could equate to millions of robots.

Modelling this demand is beyond the scope of this report, but we do feel it shows the possibility for the number of robots deployed globally to be potentially higher than our 4.1bn estimate by 2050.

Also, beyond the scope of this report, readers may want to ponder several related questions:

1. Other than large capital outlays, what could be the other constraints on countries building armies of military robots?
2. Given military AI is outside the scope of many AI regulations, including the EU AI Act, how will this area be governed globally?
3. What cyber security risks and solutions could come from AI-enabled robots moving around countries?

Additional AI risk considerations are covered in the challenge chapter of this report.

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[94] Trends in world military expenditure, 2020 https://www.sipri.org/sites/
[95] World – Armed Forces Personnel https://tradingeconomics.com/world/
[96] Armed forces of the U.S. - statistics & facts https://www.statista.com/
[97] Census of State and Local Law Enforcement Agencies, 2018 – Statistical Tables https://bjs.ojp.gov/library/
[98] List of countries and dependencies by number of police officers https://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by_number_of_police_officers
[99] 20 million private security workers https://www.forbes.com/sites/niallmccarthy/2017/08/31/

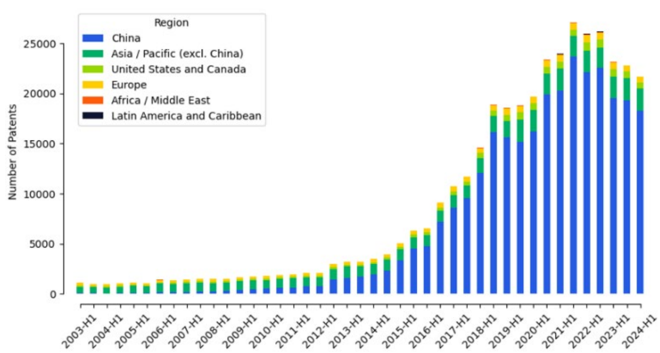
Capital / Patents

To better understand how the earliest stages of robot innovation are developing around the world, Citi Global Data Insights (CGDI) conducted a proprietary analysis of patents in the robotics field. They then compared this with recent job postings sourced from Revelio to assess how these innovations could be translated into future commercial opportunities by the patent holders. This is followed by a discussion of Venture Capital flows into this sector.

CGDI looked at patent application filings semi-annually over the last 20 years (2003-2024) sourced from QuantIP to understand innovation trends in robotics.

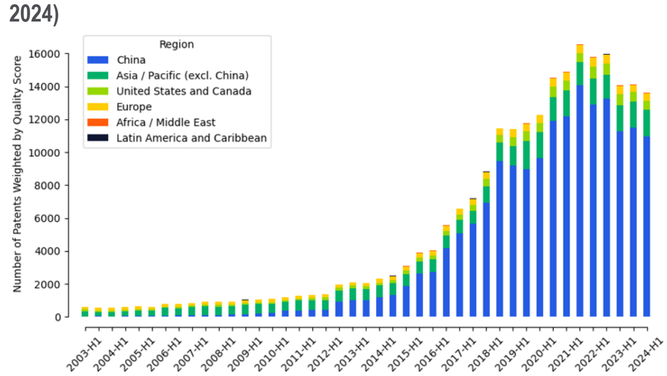
Looking at the number of new patents reveals a sharp rise in robotics publications over the past decade. This growth has been primarily generated in China, which accounts for 78% of all robotics patents over the past two decades. Japan and South Korea follow, making up 7% and 5% respectively, while the US contributes just 3%, highlighting the strength of robotics innovation in Asia. There was a 12% reduction in robotics patents between 2022 and 2023. Normalising this over the total number of patents worlwide in the same period reveals that this was also a decrease of 16% relative to the total global patent numbers.

Figure 55. Number of Robotics Patents by Region (2003 – 2024)



Source: Citi Global Data Insights, QuantIP

Figure 56. Quality Weighted Robotics Patent Count by Region (2003-2024)



Source: Citi Global Data Insights, QuantIP

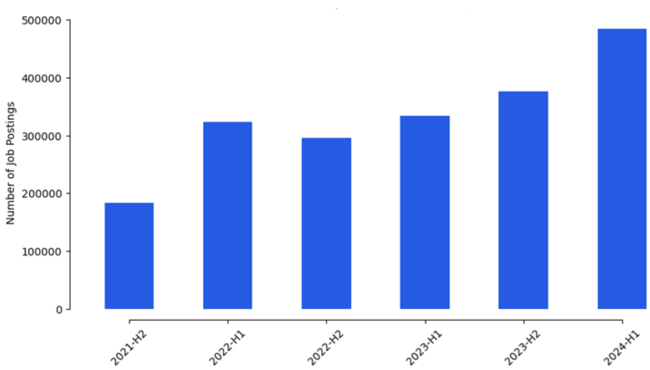
To mitigate the risk of inflated patent counts due to low quality patents, the number of patents was then weighted by the quality score (provided by QuantIP) of the patents for each semi-annual period. China's dominance remains just as strong after this weighting, indicating China's lead in both quantity and quality of robotics innovation.

When examining the entity types that created the patent applications and the sectors they operate in, private companies significantly surpass public companies and educational institutions in the number of patents produced. However, in recent years this gap has narrowed, indicating that the overall dip in robotics patents since 2022 comes as a result of decreased activities from private companies.

Breaking this down further to look at the sectors of the public and private companies, the data shows a recent decrease in patents from companies in the manufacturing sector in line with the overall robotics trend, while consumer sectors are seeing a steady growth. Since 1H 2021, Producer Manufacturing patents have reduced by 22% compared to a growth of 19% and 22% in Electronic Technology and Health Technology, respectively. This contrasting growth indicates that, while the number of patents for industrial robotics remains high, consumer electronics and healthcare sectors are seeing a stronger growth of innovation in robotics.

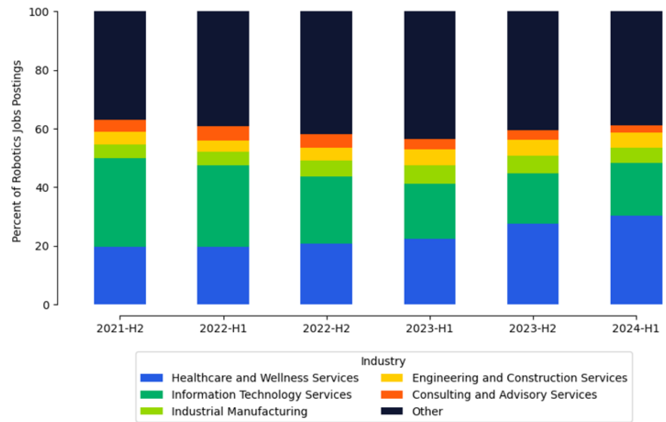
To assess whether the recent dip in total robotics patent applications signifies that there has been reduced industry interest in robotics, we examine new job postings relating to robotics over this period. The chart below shows significant job growth since 2H 2021. The total number of new job postings in robotics has seen 65% CAGR up to almost 500,000 new job postings in 1H 2024.

Figure 57. Number of Robotics Related Job Postings



Source: Citi Global Data Insights, Revelio Labs

Figure 58. Percent of Robotics Jobs Postings by Industry (%)

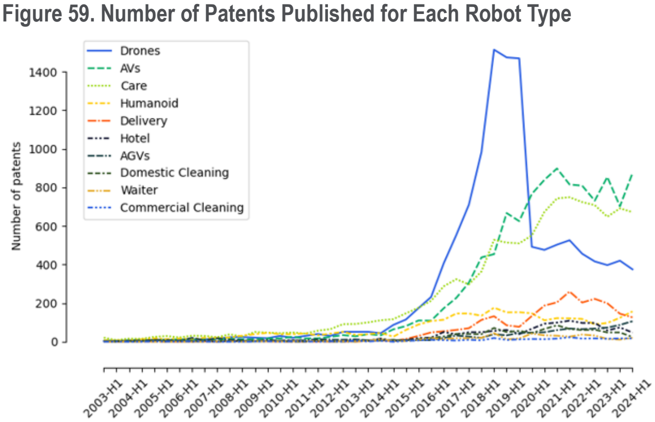


Source Citi Global Data Insights, Revelio Labs

Delving deeper into this, the breakdown by industry shows that there has been a marked increase of 54% across Healthcare and Wellness Services in the last few years, while Information Technology Services has decreased by 40%.

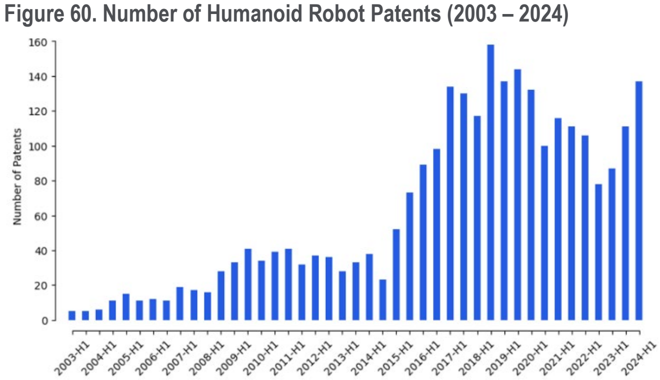
To understand patent creation across different types of robots, we categorise the patents by 10 use-cases. Attributing each patent to a particular type of robot can be challenging since many of the innovations are not necessarily intended for a specific type of robot. For example, certain sensors, actuators, controllers, and end-effectors may not be directly attributable to a delivery robot and could also be used in a robot designed for care or restaurant waitering. Consequently, to ensure high precision when linking patents to types of robots, we focus on the smaller set of patents that can be directly linked to each purpose based on the language used in the application.

Figure 59. Number of Patents Published for Each Robot Type



Source: Citi Global Data Insights, QuantIP

Figure 60. Number of Humanoid Robot Patents (2003 – 2024)



Source: Citi Global Data Insights, QuantIP

The trends we see highlight the more mature robot use-cases such as autonomous drones and AVs. There was particularly high innovation interest in drones in the period of 2018-19, mainly driven by a handful of companies. However, since that period, patent applications have fallen while autonomous vehicle and care-related robot innovations have plateaued.

When we instead focus on humanoid robots, which have historically had lower numbers than those of the more mature use-cases, we see that the trend over the last couple of years is inverse to the general trend across robotics, witnessing high growth since 1H 2022. The patents that fall into this more niche field of humanoid robots make up just 0.7% of the total population of robotics patents, but growth is significantly higher.

These patent filings provide subtle hints that humanoids appear to be gaining in terms of R&D interest, but the signals are not conclusive. Accordingly, we again take a second view looking at job postings that directly reference humanoid or anthropomorphic robots. Over the last 2.5 years since 2H 2021, the number of humanoid job postings per Revelio data (Figure 57) has grown significantly faster than those of the general robotics field at 177% CAGR, equating to an 88% CAGR relative to all robotics-related job postings.

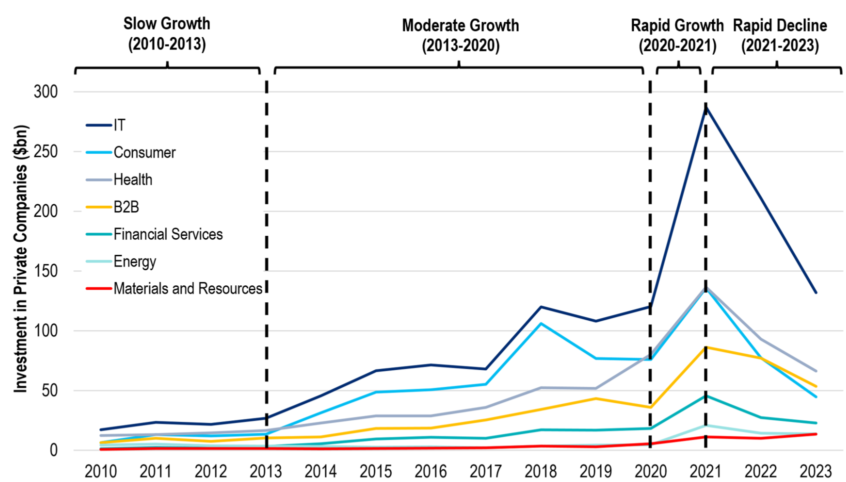
Venture Capital Flows

To understand trends in VC investment within the robotics sector, it's important to first understand the overall longer-term trends in VC investment globally.

Overall VC Investment Trends

Historically low interest rates since the Global Financial Crisis led to a rise in VC investment. VC investment grew 7x from $49 billion in 2010 to $340bn in 2020[100]. Then, emergency interest rate cuts in response to the covid-19 pandemic led to a further surge to $723bn in 2021. This meant that in total, investment by VC funds increased by 14x during the period 2010-2021.

Figure 61. Overall VC Investment over Time



Source: Citi GPS, PitchBook Data Inc

[100] All historical data in this section comes from PitchBook Data. Full year 2024 data is derived by pro-rating 1H24 data.

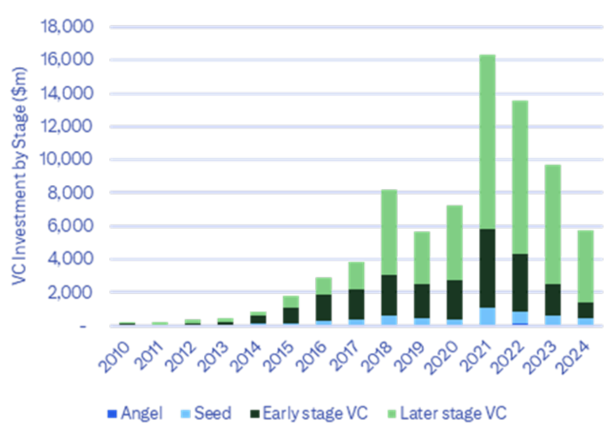
There was then an initial 30% decline in 2022 to $510bn, followed by a further 32% decline in 2023 to $346bn – just slightly higher than 2020, which itself was on par with 2018. This most recent period of rapid decline (2021-2023) in VC investment came amidst geopolitical tensions resulting in rising energy prices and inflation which had a knock-on effect of raising interest rates and declining VC investment. Consequently, whilst changes in levels of VC investment varied from sector to sector, the technology sector specifically was down 38% Year-on-Year (YoY) in 2023.

Robotics VC Investment Trends

VC investment in robotics grew more than 40x from around $180m in 2010 to $7.5bn in 2020, before more than doubling to $16.5bn in 2021, equating to a more than 90x increase over the period 2010-2021. One of the likely reasons for this surge in investment into robotics was the declining cost of developing complex robotics, as mentioned earlier in the report.

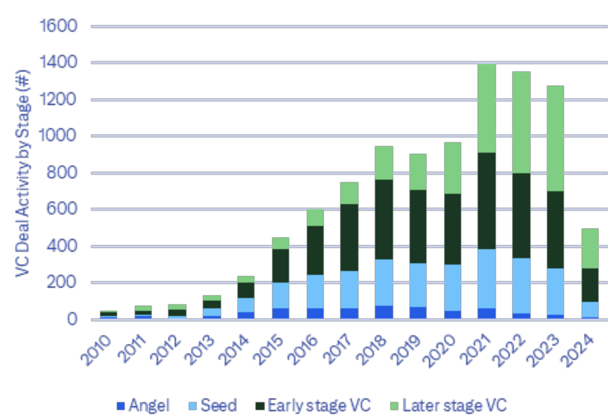
Despite this, VC investment in robotics declined a total of 40% from 2021's peak to around $10bn in 2023, broadly in-line with the technology sector overall.

Figure 62. Robotics VC Investment over Time by Stage



Source: Citi GPS, PitchBook Data Inc

Figure 63. Robotics VC Deal Activity by Stage



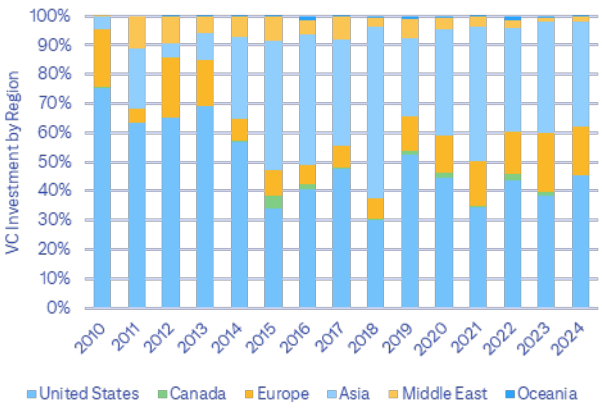
Source: Citi GPS, PitchBook Data Inc

Looking at a breakdown of VC investment in Robotics by stage (Angel, Seed, Early-Stage VC, Later Stage VC), we see that Later Stage VC has increasingly made up a higher proportion of the levels of VC Investment.

Whereas only 30-40% of the dollar-amount of robotics-related VC investments in the first half of the last decade were categorized as "Later Stage VC", this has changed to 70-80% in recent years.

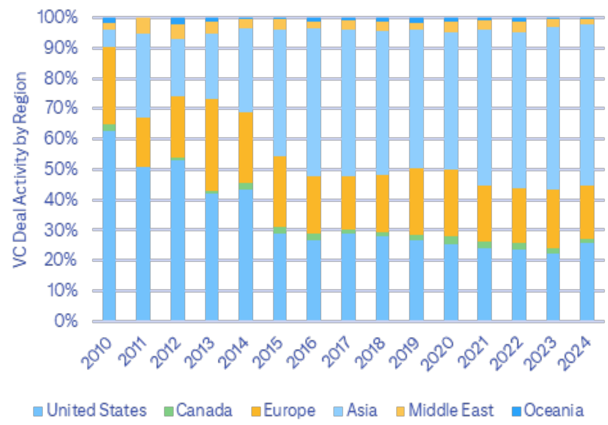
When looking at deal activity (as measured by the number of deals annually), we see a similar trend, with an increase until 2021 and a decrease since. However, despite this recent decrease, deal activity remains high. From 50-100 deals annually at the start of the last decade, deal activity experienced a more than 10x increase, to consistently 1000+ these past few years.

Figure 64. Robotics VC Investment by Region



Source: Citi GPS, PitchBook Data Inc

Figure 65. Robotics VC Deal Activity by Region



Source: Citi GPS, PitchBook Data Inc

While the U.S. averaged 66% of global VC investment in the early 2010s, it now averages around 45%. During this time, we can see how Asia has increased its global share from an average of 13% to 38%.

When looking at the deal activity over the same period, the role of Asia is clearer, from around 10-20% at the beginning of the past decade to now accounting for around 50% of all global deal activity in recent years. Similarly, the U.S.' dominance in robot-related deal activity has fallen from 50-60% to 20-30%. In that sense, changing trends in deal activity could be considered as a precursor to changing trends in the dollar-amount of VC investment.

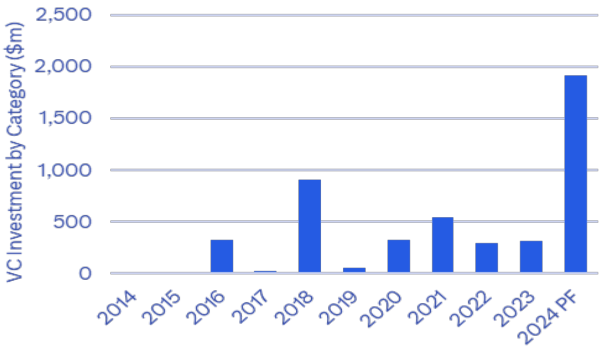
Robotics Sub-Categories

To determine what's driving many of the trends within the robotics VC investment space, we looked at what PitchBook refers to as "Emerging Spaces". These inherently have some overlap and do not necessarily add up to 100%, but they do show an interesting story.

Humanoid robots have seen a significant increase in VC Investment. The first 6 months of 2024 has seen almost $1bn raised – more than the total of any previous year. At this rate, it implies a 500% increase for the full year 2024 compared to 2023. This was the most VC investment raised of all the robotics-related subcategories that we looked at.

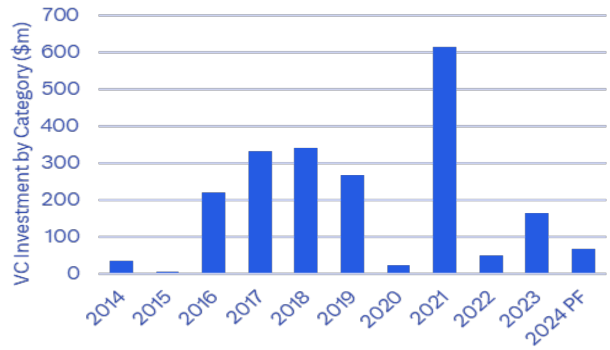
Another impactful area for robotics is in the medical field. As mentioned earlier in this report, robots like the da Vinci Surgical System have already been FDA-approved to be used in surgical procedures. Interestingly however, investment in this space has been sporadic, with some years only experiencing VC investment in the low 10s of millions, with other years experiencing 100s of millions. Investment peaked in 2021 at $600m, likely due to the pandemic, but declined almost 90% since then to an estimated $70m for 2024.

Figure 66. Humanoid Robotics VC Investment



Source: Citi GPS, PitchBook Data Inc

Figure 67. Medical Robots VC Investment



Source: Citi GPS, PitchBook Data Inc

Construction Robots saw both significant increases and decreases in recent years, broadly in line with overall investment into robotics. Investment increased significantly at the beginning of this decade, to a peak in 2022 of $270m, but has since decreased more than 85% to a forecast $40m for 2024.

On the other hand, the Food Service Robots & Machines subsector has seen relatively consistent VC investment in recent years. Despite changes in the overall landscape, as well as that of robotics in particular, PitchBook data shows investment has mostly remained in the $80-120m range since 2017.

Other categories, such as Robotic Process Automation, while not a type of robotics, also increased significantly over the past decade. For instance, investment increased 25x from around $40m in 2014 to almost $1bn in 2021 but has since decreased more than 25x to a forecast $35m for 2024.

Overall VC investment in robots remains strong. However, there are significant differences when looking at the spread of this spending globally and by subsector, driven by changes in technology and also public interest in certain areas.

Challenges

The first chapter of this report highlighted technological advances which should accelerate the adoption of AI-enabled robots. The subsequent chapters dug into some of the use cases and the potential size of some big new markets over the next 25 years.

Aleksandra Faust
Director of Research
Google DeepMind

What are the main challenges you see ahead for the progress or adoption of AI Robots?

AI has made remarkable advancements in recent years. Large Language Models simplified human-robot communication, while Foundational Models unlocked new levels of generalization and learning abilities. These innovations have paved the way for the development and widespread adoption of general robotics applications.

However, significant challenges still need to be addressed to bring robotics to the real world on a large scale. First, while robots have potential to perform tasks beyond human capabilities, address labor shortages, and augment humans in various applications, adoption depends on identifying applications that are both compelling and economically viable at scale.

Second, the development of robotics system components, including software, hardware, and chips, largely occurs in isolation, risking over-designed components and costly system development and integration. An application-first approach to the entire system design, encompassing software, hardware, and chip design, where all system components are co-designed together, can facilitate the creation of scalable physical systems.

Last, natural and safe human-robot interaction in dynamic, unstructured environments is crucial for successful robot deployment in the real world. Human-Robot Interaction (HRI) research focused on intuitive communication and collaborative task execution, fueled with advancements in Large Language Models, will make robots accessible to the non-technical population.

Overall, this is an exciting time for robotics. The recent progress in AI provides the essential building blocks to address long-standing challenges in system design and robot-human interaction, which historically prevented robots from ever leaving the labs.

Are there other potential wild cards that keep you up at night?

Addressing ethical considerations and potential socio-economic impacts, such as workforce displacement and algorithmic bias, will be paramount. A commitment to ethical development and deployment, ensuring equitable access and responsible use, will be vital for harnessing the transformative potential of AI robots for the benefit of society.

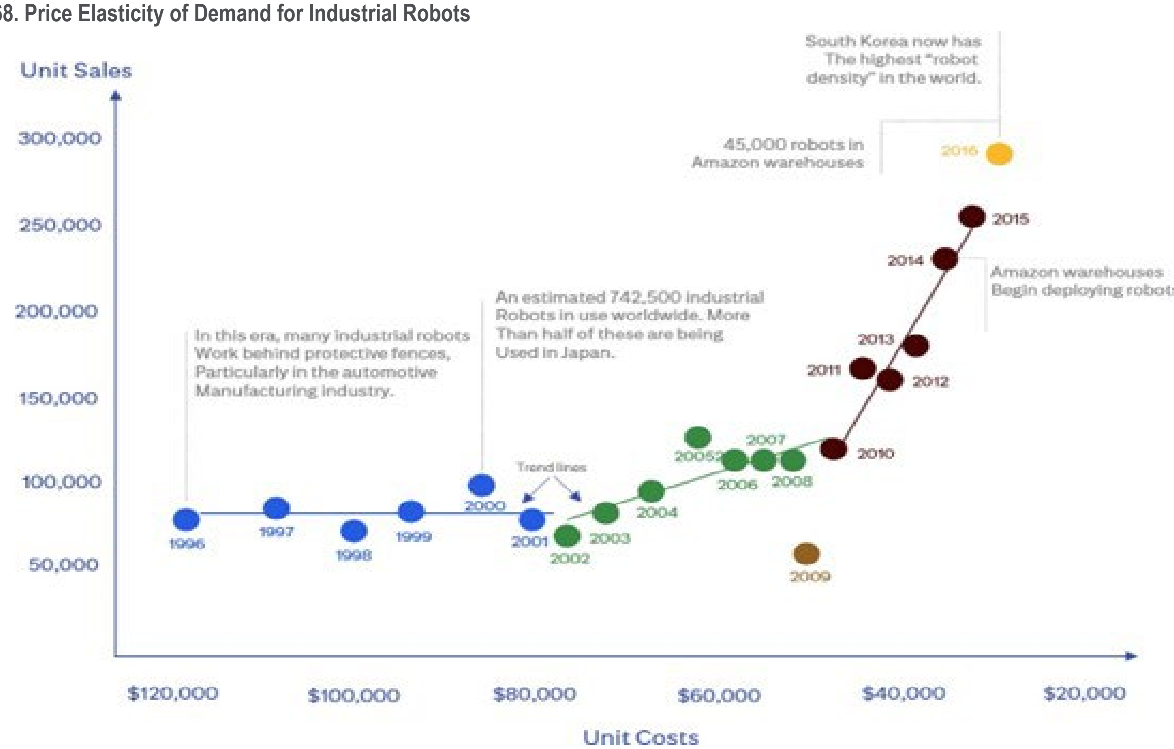
There are however several significant challenges that AI-robots must overcome before seeing mass adoption. We identify 12 of these next.

1. Manufacturing Costs

One of the most significant challenges facing widespread adoption is the current high manufacturing cost of robots. While long-term economies of scale are likely to drive prices down – robot prices in the U.S. have already halved since 1990, even as labor costs have doubled – the near-term cost barrier remains substantial.

One of the reasons we analyze high penetration of domestic cleaning robots is their affordable prices. According to Euromonitor the average price for a robot vacuum cleaner is $436. However, the increased sophistication and capability of other robots comes with higher costs. For example, Boston Dynamics' robot dog costs around $75,000. The cheapest humanoid robot we have found on the market is Unitree's G1 priced at $14,000, but according to China's Blue Book the average humanoid price is $86,000.

Figure 68. Price Elasticity of Demand for Industrial Robots



Source: Visual Capitalist

The impact of cost reductions on adoption rates is evident when examining the sales of industrial robots, as shown above. It wasn't until unit costs fell below $50,000 in the 2010s that unit sales of industrial robots began to increase.

Given high costs of building, purchasing, and maintaining robots, access to capital could be a crucial factor in determining which companies can effectively leverage these technologies. Larger companies with deep pockets and the ability to achieve economies of scale are often better positioned to invest in robotics.

The ability of larger companies to absorb the high costs of robotics gives them a competitive advantage, allowing them to experiment, innovate and optimize their operations in ways that smaller companies may struggle to do.

China's industrial strategy includes building a world class robot ecosystem and there is a great deal of robot innovation taking place in China. If subsidies are used, or a low ROI over a long period of time is acceptable, this could impact the economics of the robot industry.

2. Robustness

As the development of humanoid robots advances, a critical challenge that manufacturers face is ensuring that these machines are robust enough to withstand collisions or fluctuating environmental conditions. While robots can be built to standards suitable for controlled laboratory environments, making commercially viable products requires durability and resilience.

To address these challenges, robots designed for commercial use must incorporate robust materials and construction techniques.

To ensure environmental resilience, manufacturers will likely need to implement protective measures such as incorporating temperature regulation systems.

The challenge of making robots robust enough for commercial use is not merely a technical one but also an economic one. Building more durable robots typically involves higher manufacturing costs due to the need for stronger materials and more complex construction methods. However, these additional costs must be balanced against the need to keep robots affordable for buyers.

Furthermore, the ability of a robot to withstand real-world conditions without frequent repairs or replacements is a key factor in its return on investment (ROI).

3. Battery Power

One of the most significant challenges in the development and deployment of autonomous robots is the issue of battery power. Modern robotics, particularly those incorporating advanced AI capabilities, are increasingly dependent on reliable and efficient energy sources.

The energy density of modern batteries, particularly lithium-ion batteries, remains a critical constraint for robotic applications. Currently, lithium-ion batteries offer an energy density of around 250 watt-hours per kilogram (Wh/kg). While this has been sufficient for smaller consumer electronics, higher energy density is important for robots to operate for extended periods without the need for frequent recharging. This is particularly needed in mobile and autonomous systems.

Compounding the issue of limited energy density is the rapidly increasing energy demand of AI models integrated into robots. While battery energy density typically improves at a rate of about 5-8% per year, the energy demands of AI models are growing significantly faster. This disparity means that, without significant advancements in battery technology, the gap between energy supply and demand will continue to widen, potentially limiting the capabilities of AI-powered robots.

AI-driven robots require substantial computational power to process data, make decisions, and learn from their environments in real-time. This computational intensity translates directly into higher energy consumption, putting additional strain on existing battery technologies.

There are promising advancements on the horizon, including graphene batteries and solid-state batteries.

By some estimates, graphene batteries are expected[101] to provide a 300-400% improvement in energy density compared to traditional lithium-ion batteries.

4. Processing Efficiency

Processing efficiency is an additional challenge for AI-Robots. The powerful processors that enable AI to perform complex calculations are also power-hungry.

The processors that power modern AI applications, particularly in robotics, are primarily built on Complex Instruction Set Computer (CISC) architecture, specifically the x86 architecture. This architecture is well-suited to handling the intricate and computationally intensive tasks required for AI processing, such as deep learning and neural network operations. But they are also power-intensive.

To address these challenges, the robotics industry may shift towards more power-efficient architectures. One alternative is the ARM's Reduced Instruction Set Computer (RISC) architecture.

Since around 2015, ARM-based chips have made significant strides in performance, improving at roughly twice the rate of x86 chips. This rapid improvement has allowed ARM processors to power high-performance devices, including the processors in Apple's latest MacBook models. The efficiency of ARM architecture not only reduces the power requirements for AI processing but also enables more compact and lightweight designs.

5. Energy Consumption

AI's rapid advances across multiple industries is creating concerns over the scale of energy consumption required to sustain this growth.

According to the World Economic Forum (WEF), the computational power required for AI is doubling roughly every 100 days. By 2027, global AI-related electricity consumption could exceed 134 terawatt-hours (TWh) annually,[102] a figure comparable to the total electricity consumption of entire countries such as Argentina and Sweden. This level of consumption underscores the urgent need for more energy-efficient AI technologies and infrastructure.

To address the escalating energy demands of AI, there is a clear need for the development of more energy-efficient algorithms. Innovations in this area could include optimizing existing algorithms for efficiency, developing new AI models that require less computational power, and leveraging techniques such as pruning or quantization to reduce the complexity of neural networks.

In addition to algorithmic improvements, the AI industry would also need to focus on the infrastructure that supports AI operations – particularly data centers. Data centers are the backbone of AI, providing the computational power and storage capacity needed to process and analyze vast amounts of data.

Efforts to make data centers more energy-efficient could involve a range of strategies, from improving cooling systems to implementing advanced energy management software.

[101] Ossila (link)
[102] The New York Times (link)

6. E-Waste

Electronic waste, or e-waste, will be another challenge for the robot industry. The disposal and recycling of e-waste from modern technology is already a significant and growing global problem. The increasing adoption of robots is likely to exacerbate this issue unless measures are taken.

In 2021, the world generated approximately 57.4 million metric tons of e-waste[103], with a substantial portion coming from electronic devices such as smartphones, laptops, and other consumer electronics. In addition to the growth in e-waste, a significant portion is not properly recycled, leading to environmental pollution and the loss of valuable materials.

The use of proprietary components adds to e-waste concerns. While AI software updates are possible, hardware updates are more difficult. Many robots are designed with specialized parts that are unique to a particular manufacturer or model. This makes repairing or upgrading robots more difficult and costly, as replacement parts may not be readily available or be expensive.

In response to the growing e-waste problem, "right to repair" movements and laws have gained momentum, particularly in regions like the European Union. These initiatives advocate for consumers' ability to repair their devices, rather than being forced to replace them.

For the robotics industry, embracing the principles of the "right to repair" could extend product lives and reduce the environmental impact of e-waste.

7. Trust

Trust is a crucial factor in the widespread adoption of any technology, and in recent years, trust in AI has notably declined. This decline is particularly concerning as the technology moves closer to more autonomous and potentially impactful forms, such as Artificial General Intelligence (AGI) and then Artificial Super Intelligence (ASI).

According to a global survey conducted by Axios[104], across 24 countries, trust in AI companies has fallen from 61% in 2019 to just 53% in 2024. In the United States, the decline has been even more pronounced, with trust levels dropping from 50% to 35% over the same period. This downward trend points to growing public skepticism about the safety, reliability, and ethical implications of AI technologies.

Several factors contribute to this declining trust. One of the primary concerns is the low level of explainability, transparency, and causality in AI systems. Many AI models, particularly those based on deep learning, operate as "black boxes," where the decision-making processes are not easily understood even by their developers. This lack of transparency makes it difficult for users to trust AI-driven outcomes, particularly in high-stakes scenarios.

Trust levels can also be influenced by the physical appearance of robots. People tend to trust robots more when they do not closely resemble humans. This phenomenon, often referred to as the "uncanny valley," suggests that robots with a

[103] WEEE Forum (link)
[104] Axios (link)

more mechanical or clearly non-human appearance are perceived as less threatening and more trustworthy.

History suggests progress will not be a straight line, but involve steps forward, sideways or even backwards. The opening of the Liverpool and Manchester Railways in 1830 was marred by a fatality but did not prevent rail adoption. The first person killed by a car was in 1896 at just 4 mph[105]. Driving licenses (1903), speed restrictions (1934), and seat belts (1983) were added over time to improve safety, yet there are still c.1.2m road fatalities each year[106]. Implementing safety measures for robots that give users more trust and control over the technology is likely prove critical to their successful integration into society. Like cars, this may be an iterative process that takes time.

8. Privacy

As robots become more integrated into everyday life, they present unique and significant challenges related to privacy and the security of information.

Robots, particularly those designed for use in homes and other personal spaces, have the potential to collect deeply personal data. This data can include not only visual and auditory information but also details about users' habits, preferences, and even biometric data. While this information can be used to enhance user experience and improve the functionality of the robots, it also presents significant risks if not properly managed and protected.

A stark example of these risks occurred in 2015, when over six million toys produced by Vtech, a manufacturer of electronic learning toys, were compromised in a major security breach. This breach gave hackers access to photos and other personal information of the children who used these toys, highlighting the vulnerability of AI-enabled devices that collect and store sensitive data.

Concerns about privacy are not limited to isolated incidents. There have been numerous reports of home CCTV systems being hacked - in one instance, for example more than 30 people lodged complaints about unauthorized access to their security cameras[107].

In response to growing concerns about data privacy, regulations such as the General Data Protection Regulation (GDPR) in the European Union have been implemented to provide a legal framework for protecting personal data.

9. Legal Accountability

As AI-driven robots become more prevalent in society, questions over legal accountability will become increasingly important. As robots take on more roles that involve decision-making and direct interaction with humans, existing legal frameworks, which were largely designed for human decision-makers, are being tested.

Not only is the environment complex and rapidly changing, but it is likely to get expensive. The EU AI Act imposes strict regulations on the use of AI, with the

[105] National Motor Museum (link)
[106] WHO (link)
[107] The Guardian (link)

maximum fines for non-compliance set at 7% of a company's global turnover – significantly higher than the 4% maximum fine under the General Data Protection Regulation (GDPR). For companies using AI in robots, this means that the EU AI Act will apply not only to the software but also to the robots themselves, adding another layer of complexity and potential liability.

A fundamental issue in the discussion of legal accountability is determining who is liable when a robot causes harm. Traditional legal frameworks assume that humans are the primary decision-makers and thus are responsible for their actions. However, as robots become more autonomous and capable of making decisions without human intervention, this assumption is increasingly challenged.

Laws will need to evolve to account for scenarios where robots, rather than humans, are the primary actors in decision-making processes.

10. Data

Data will influence trust, regulations and legal frameworks. Data is also critical to AI systems. One of the most significant challenges facing the deployment of AI-driven robots in real-world environments is the availability and quality of training data.

The success of AI-robots, especially in high-stakes applications, depends heavily on their ability to learn from vast amounts of accurate and relevant data. However, the current state of data collection presents a "chicken and egg" dilemma: we need more robots in the real-world to collect data, but we need more data to allow robots to operate safely in the real-world.

Autonomous vehicles are a current example of this dilemma in training robots. Given the high stakes environments, autonomous vehicles (AVs) must be trained on millions of miles of driving data to handle the vast array of scenarios they might encounter on the road. Despite technological advances, without more AVs being allowed to drive on our roads, it is difficult to gather the necessary data to train them. Without significant training, AVs may not be advanced enough to be deployed safely at scale. The high-stakes healthcare sector may face the same issues.

Collecting real-world data is a challenging and resource-intensive process. Unlike controlled lab settings, the real world can be chaotic, with countless variables and unpredictable events that can impact data quality. For instance, autonomous vehicles collecting driving data must navigate a constantly changing landscape of road conditions, weather patterns, and human behavior.

Moreover, the collection of real-world data often requires substantial financial investment. Gathering vast amounts of data can take years and require significant resources, potentially slowing development and benefiting companies with deeper pockets.

The pace of this data collection process also varies depending on regulatory environments. However, this approach also comes with risks, requiring a balance between fostering innovation and ensuring appropriate safety and reliability of AI-driven robots.

11. Infrastructure

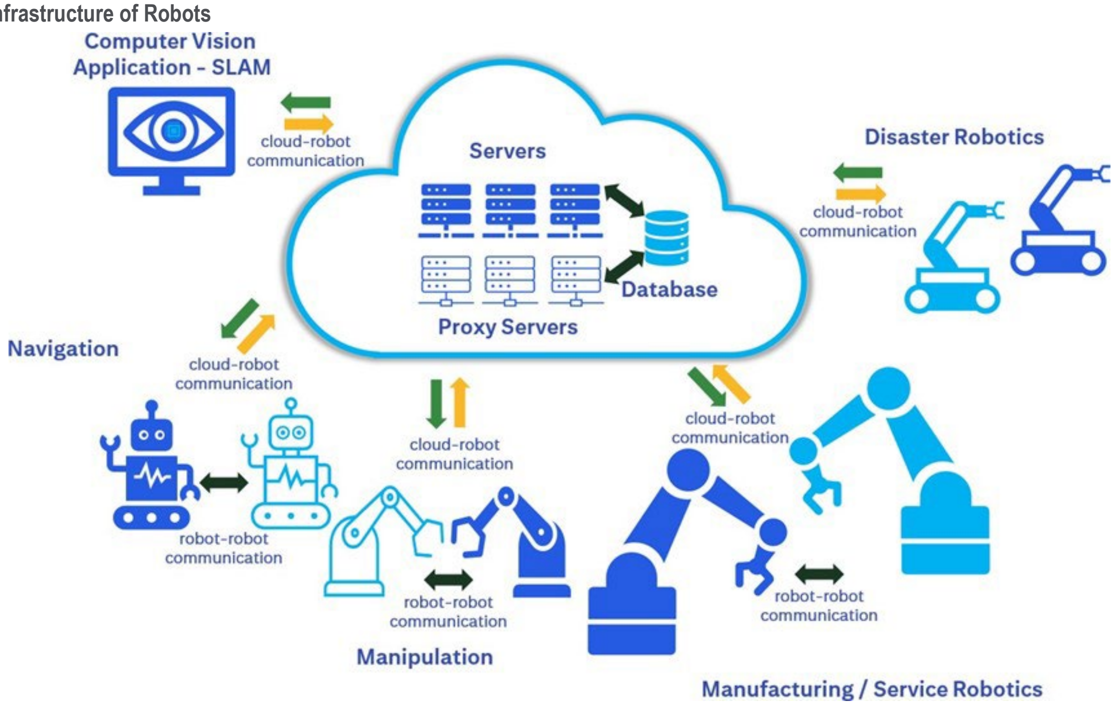
The widespread adoption of robots in various sectors needs to happen in parallel with the necessary infrastructure to support their deployment, maintenance, and operation.

One infrastructure component required for robot adoption is the establishment of charging stations. Just as electric vehicles (EVs) have necessitated the installation of a vast network of charging points, so too will robots require dedicated charging infrastructure.

The experience with EVs demonstrates that building a network of charging stations can be complex, requiring planning, investment and coordination between various stakeholders, including government agencies, utility companies, and private sector players. For robots, charging stations will need to be strategically located to ensure accessibility and convenience.

As the adoption of electric cars and AI technologies increases, electricity grids in many regions are already struggling to keep pace with demand. The addition of a significant number of robots that require regular charging could place further strain on electricity grids. Expanding and upgrading utility power infrastructure could be needed, but such projects are complex and take considerable time to implement.

Figure 69. Infrastructure of Robots



Source: Citi GPS

In addition to charging infrastructure, the mass adoption of robots will necessitate the establishment of service repair centers and robot maintenance shops. Just as automotive service centers are crucial for maintaining vehicles safely, robotic service centers will play a vital role in the lifecycle management of robots.

The creation of such service infrastructure will require a workforce of sufficiently trained engineers who can install, operate, and maintain these systems. Despite a global push towards promoting careers in engineering and technology, the robotics industry continues to face a shortage of skilled workers. This shortage is even more pronounced when considering the need for diverse talent.

The skills gap is likely to slow the pace of development and will require collaboration between educational institutions, industry leaders, and government bodies to develop targeted training programs and initiatives. Robot vocational training and apprenticeship programs to provide hands-on experience and practical knowledge can help bridge the gap between academic learning and industry needs.

In conclusion, the mass adoption of robots will require a comprehensive and well-planned infrastructure ecosystem, including charging stations, service repair centers, sufficient power, electricity grid upgrades and workforce development.

12. Job Security

As robots become increasingly intelligent, dexterous, and mobile, they are rapidly assuming roles traditionally performed by humans. It is important to note that our forecasts for AI-robots include many areas which will create more time for humans rather than substitute for jobs, such as driving your car or cleaning your home. However, this transition also raises critical concerns about job security, particularly in industries where robots may substitute for human labor, such as taxi drivers or commercial cleaners. Understanding the potential impact of robots on the workforce is essential as we move toward a future where automation plays a central role in economic activity.

One of the most significant opportunities presented by robots is their ability to perform tasks in areas where there is a shortage of qualified or willing employees.

A preview of this future can be seen in sectors like automotive manufacturing, where robotic assembly lines have already displaced significant numbers of workers. One MIT study of robot adoption in the US between 1990 and 2007 concluded that each robot replaced 3.3 workers[108].

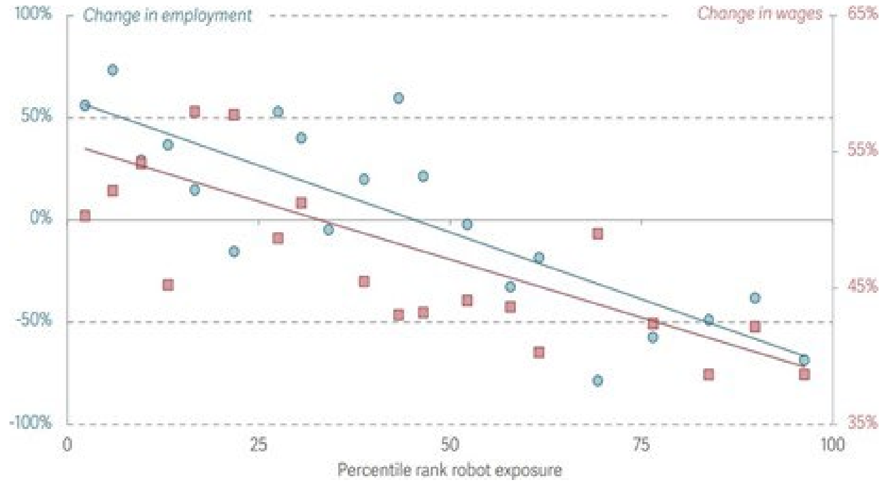
The cost dynamics of robots are a crucial factor in determining their impact on job security. Historically, the cost of robots has been declining as technological innovation and manufacturing economies of scale improve. As shown above, robot costs have fallen by 50% since 1990, while wage costs have increased materially during the same period.

Consider the economics of humanoid robots as an example. If a humanoid robot were to cost $20,000 –and work 16 hours per day (given charging times), six days per week (to allow for maintenance), at the equivalent of a US minimum wage of $7.25 per hour, the payback period would be just 29 weeks.

The adoption of robots has several implications for the labor market. In addition to substitution concerns, the introduction of robots into various markets over the last 40 years has tended to suppress wages for human workers. This trend is expected to continue with the deployment of AI-powered robots, as digitization generally exerts disinflationary pressures.

[108] https://news.mit.edu/2020/how-many-jobs-robots-replace-0504

Figure 70. Changes in employment and wage growth between 1981 and 2019 by percentiles of robot exposure



Notes: Binscatter plot of change in employment measured as DHS change of each occupation share of employment between 1981 and 2019 and the change in wages measured as DHS change in each occupation mean full-time weekly wage. Percentile rank of robot exposure is calculated as the employment weighted percentiles of the corresponding exposure score according to the 1981 employment occupational structure

Source: CEP analysis of LFS, ASHE and Michael Webb (2020), The Economy 2030 Inquiry, Resolution Foundation

However, the relationship between robots and job security is complex. While some roles may be displaced by robots, the adoption of these technologies can also create new job opportunities such as robot maintenance technicians, AI system trainers, and data analysts who can interpret the data generated by robots.

To mitigate the impact of job displacement, there is a critical need for targeted reskilling programs that help workers transition from old to new roles. Governments and industry leaders will need to work together to develop training initiatives that equip workers with the skills needed to thrive in an increasingly automated world. For example, the European Union's Digital Skills and Jobs Coalition aims to train 20 million people in digital skills by 2030.

In addition to taking on tasks that were previously uneconomic, robots have the potential to enhance job quality by taking on more mundane or physically demanding tasks, allowing humans to focus on more complex, human facing, or creative aspects of their work.

Proactive measures such as targeted reskilling programs and supportive government policies, can help manage the transition to a more automated robot economy in a way that benefits workers and society. For a more detailed exploration of AI's impact on work, please see our recent CGI reports "AI Doom vs Boom for Jobs" and "What Machines Can’t Master: Skills to Thrive in an AI Age"

Conclusion

So, what did we learn along our journey for this report?

1. Rapid technology advancements, particularly in AI, are taking place and coming together.
2. Some markets are already rising quickly (e.g. cleaning) while others could be at the bottom of the S-Curve (e.g. AVs).
3. Consumers are likely to welcome AI-robot's that save them time - from cleaners, to chauffeurs, butlers, carers, or personal assistants.
4. Businesses are likely to welcome AI-robots that: reduce staff shortages, particularly as immigration restrictions rise and populations age; help as supply chains are reconfigured post the pandemic and as geopolitical risks rise; and offer short payback periods versus human labor.
5. Unit forecasts for robot deployment vary widely by sub-sector but aggregate to 4.1bn by 2050 based on our forecast. Note we analyzed 9 primary areas (with humanoids then broken down into 7 sub-markets) but did not include robots used in security, military, safety, education, or agriculture.
6. We did not analyze ASPs for most markets, and they will vary greatly, but doing so for humanoids suggested a possible $7trn TAM. Some very large new markets are being born.
7. Given the large economic opportunity for AI-robots, capital is flowing into this area. This will provide further fuel for innovation, production and adoption.
8. The sub-title of this report - AI Robots are coming for you - is a nod to the importance of data for personalization, usefulness, scale-led cost reductions and regulatory approvals. Like the early days of the internet, and winner-takes-most economics of digitizing businesses, we suspect that the battle to be your robot will be led by companies (or countries) with deep pockets.
9. China is leading in several areas, such as: industrial robot installations; innovation patents; and price reductions.
10. Robots are likely to be a deflationary force for wages and interest rates.
11. While many challenges remain, we suspect these will vary by market - such as regulatory approval for AVs or the use of personal data. Significant open questions, such as use in military settings or AI-alignment, remain.
12. AI-robots may create new roles (e.g. maintenance), augment roles (e.g. safety robots) or substitute roles (e.g. taxi drivers). We analyzed a 1-1 rate of substitution, but this is up for debate. Given significant change lies ahead and AI-robots will not hang around waiting for workers to catch up, we would point proactive readers to our recent GPS report 'What Machines Can't Master.'

Go well - AI-Robots are Coming.

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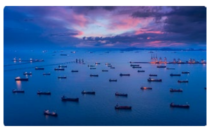

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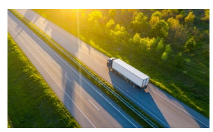

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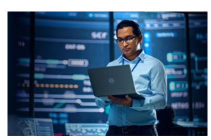

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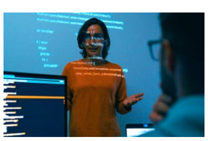

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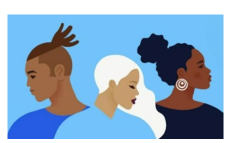

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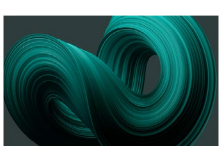

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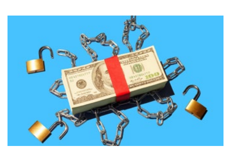

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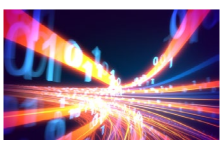

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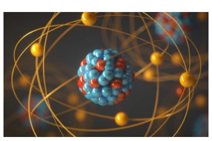

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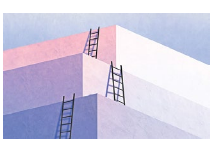

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