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Transformation

Humanoid robots 101

29 April 2025

Key takeaways

- Is the era of the humanoid robot upon us? Global tech giants have all begun to develop humanoid robots (HRs), and with such heavyweight support, BofA Global Research believes HRs are poised to move from proofs of concept to multi-industry adoption by the end of the decade.
- How? Humanoid robot development may start to pick up speed up with the help of 1) robust AI development worldwide; 2) more advanced 3D perception and control technologies; and 3) a decline in the costs of computing power and robot components.
- But before there are as many humanoid robots as there are cars, let's get to know the future robot next door - what makes them different than industrial robots, what components go into making them, what might they cost and what needs to happen to achieve mass adoption?

Compute this: Humanoid robots are on the way

Humanoid robots (HRs), have made huge developmental strides in recent years, driven by the surge of AI technology, especially the continuous iteration of large language models (LLM) and visual language models (VLM). While tech giants have begun to develop HRs, other HR start-ups have also joined the fray in recent years along with existing industrial robot and automobile OEMs (original equipment manufacturers). Given the support and added focus on the development of HRs, BofA Global Research believes HRs are poised to move from proofs of concept to multi-industry adoption by the end of the decade with improved robot designs and wider applications as well as an increasing number of new entrants joining the competition.

But what is a humanoid robot? It's a type of service robot that mimics a human's behavior and interactions. It is typically designed to replace human workforces in dull, dangerous and/or unhygienic working environments, but unlike industrial robots that operate in a highly structured and uniform environment, humanoid robots commonly work in an unstructured environment with a high level of uncertainties. Typical applications of humanoid robots may include security, healthcare and warehouse management. They can also be used in household applications such as taking care of the elderly or doing housework (see our recent piece, Housework: When time is money, for more on this topic).

But compared to other types of robots, humanoid robots usually face more complex working environments, which requires sophisticated AI functionality to support their sensing, motion control and interactions with humans (Exhibit 1). They also have a higher level of flexibility than typical service robots, usually with >20 degrees of freedom (DoF, or a way to explain the motion capabilities of a robot) and can perform various (usually unstructured) tasks. This translates into higher requirements of motion control, and limits in the height and weight of humanoid robots.

Exhibit 1: Humanoid robots usually face a more complex, unstructured working environment
Comparison between humanoid robots and industrial robots

	Humanoid robot	Industrial robot
Tasks	Multifunctional in daily tasks, including interaction with human	Repetitive tasks such as welding, assembly and packaging
Working environment	Unstructured	Structured
Structure	Complex	Relatively simple
Degree of freedom	>20	up to 6
Mobility	Usually bipedal	Fixed
Precision requirement	Medium for general tasks	Relatively high
Application	Service, manufacturing, education, elderly care etc.	Industrial manufacturing
Selling price	US$15k - 250k	US$2k - 60k

Source: BofA Global Research

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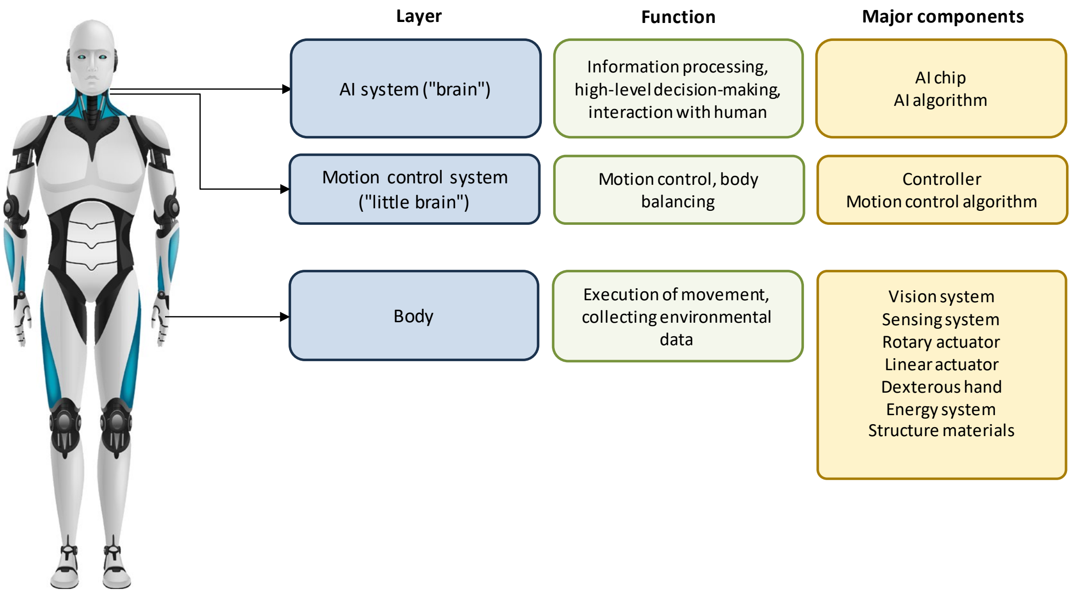
The building blocks of a bot

The structure of a typical humanoid robot can be divided into three major layers: AI system, motion control system and robot body (Exhibit 2):

- **The AI system** is the "brain" of the humanoid robot, mainly comprised of the AI chip and AI algorithm. It oversees high-level information processing and decision making (including task decomposition, understanding surrounding environment and model inference etc.), as well as interaction with humans.
- **The motion control system** is the "little brain" of the humanoid robot, and mainly includes controller and motion control algorithm. It is largely in charge of motion coordination, body balancing and route navigation.
- **And the body** contains major hardware used for environmental data collection and execution of movement, including the vision system, sensory system, actuators, dexterous hand, energy system and structure materials.

Exhibit 2: The structure of a typical humanoid robot can be divided into three major layers: AI system, motion control system and robot body

The structure of a humanoid robot



Source: BofA Global Research

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Control system

The control system of a humanoid robot includes two layers: an AI system in charge of high-level control (information processing, decision making), supported by AI chips and AI algorithms; and a motion control system in charge of lower-level control, such as motion coordination and body balancing, supported by controllers and motion control algorithms.

- **Chips:** The chips used in HRs mainly include processor chips, control chips and bus management chips. Among them, processor chips form the core of the "brain" of a humanoid robot, mainly used for model inference and computation. Currently, the mainstream technology for HR processor chips is the CPU (central processing unit) plus GPU (graphics processing unit) structure, which is also the most mature technology.
- **Control algorithm/embodied AI:** Control algorithms are the core of an HR's control system, enabling the robots to perceive the environment, process vast amounts of sensory data, make real-time decisions, and execute actions. The traditional control algorithm of humanoid robots takes a hierarchical approach between the AI system ("brain") and the motion control system ("little brain").

  On the other hand, some leading humanoid robot companies are now migrating to an end-to-end model, which directly generates action instructions based on the sensory data input (including vison, language, force etc.), without the need for complex intermediate processing steps and achieved by a single neural network. Compared to the hierarchical approach, an end-to-end model has the advantage of strong generalization ability, higher efficiency and less requirements on feature engineering. That said, it usually requires larger amounts of training data, which could be a bottleneck in the near term.

Actuator module

The actuation system is the core component for the motion control of humanoid robots. There can be electric, electro-hydraulic and pneumatic actuators, all of which move or control components in a system by converting energy into physical motion. Electro-hydraulic actuators have the highest output torque but are also costly and have the risk of oil leakage. Pneumatic actuators, on the other hand, are less expensive but also have lower precision and output force. Electric actuators have now become the mainstream technological route for humanoid robots, thanks to their high precision, fast speed and reasonable price.

An electric actuator comprises a servo drive for motion control, a servo motor (usually frameless torque motor) for torque output, a transmission system (harmonic/planetary reducer for rotary actuator, and planetary roller screw for linear actuator) to convert the torque for desired use, and a sensory system (encoder and torque/force sensor) to collect system data. Depending on the usage, electric actuators can be categorized as either a rotary actuator or a linear actuator, used in rotary joints (neck, shoulder, wrist, elbow, etc.) and linear joints (arm, ankle, knee, etc.) of the robot.

Dexterous hands

Dexterous hands are a key end-effector of humanoid robots, which can perform complex and delicate tasks, including picking up small items and handling fragile objects. Currently, the design of dexterous hands by different humanoid robot OEMs ranges from 6 to 42 degrees of freedom (DoF), versus 27 DoFs of a human hand. Generally speaking, a 6-DoF dexterous hand design can support 60-70% of the functions of human hands.

Reducers

Reducers are mechanical devices used in humanoid robots, industrial robots and machine tools to reduce the speed and increase the output torque of a motor or engine. There are mainly three types of reducers: planetary reducers, harmonic reducers and RV (rotate vector) reducers. Currently, mainstream humanoid robot design adopts either harmonic reducers or planetary reducers for its rotary actuators.

Planetary roller screw

Planetary roller screws are high-performance mechanical components used in the linear actuators to convert rotational torque output from the servo motor into linear motion. Compared to ball screws, planetary roller screws have the advantage of longer lifespans, higher loads, higher transmission efficiency and higher rigidity. As such, planetary roller screws are usually used in humanoid robots, aerospace and heavy-load machine tool industry.

Frameless torque motor

A frameless torque motor is a type of permanent magnet electric motor. Compared to traditional motors, it consists solely of a rotor and stator, without a frame, housing, shaft, bearing or feedback system, which eliminates the need for mechanical transmission components like gears or shafts, driving the load directly via magnetic interaction. This can achieve high torque density and high dynamic performance within a compact structure and are therefore often used in applications where high torque and low-speed performance are critical, such as robotic joints, medical equipment, and aerospace systems.

Sensory system

The sensory system of a humanoid robot collects data from the surroundings, which feeds to the motion control module to adjust the robot's motion. It includes cameras, LiDAR (light detection and ranging) and various types of sensors. The number of sensors in a humanoid robot may range from 30 to 200, depending on the function of the robot.

- **Vision system:** Humanoid robots' vision system is a complex and intelligent system that uses various types of cameras and LiDAR to capture visual information of the surrounding environment, which enhances the robot's sensing, navigation and motion control capabilities. Major technologies include a stereo camera, a time of flight (ToF) camera, a structural light camera and LiDAR.

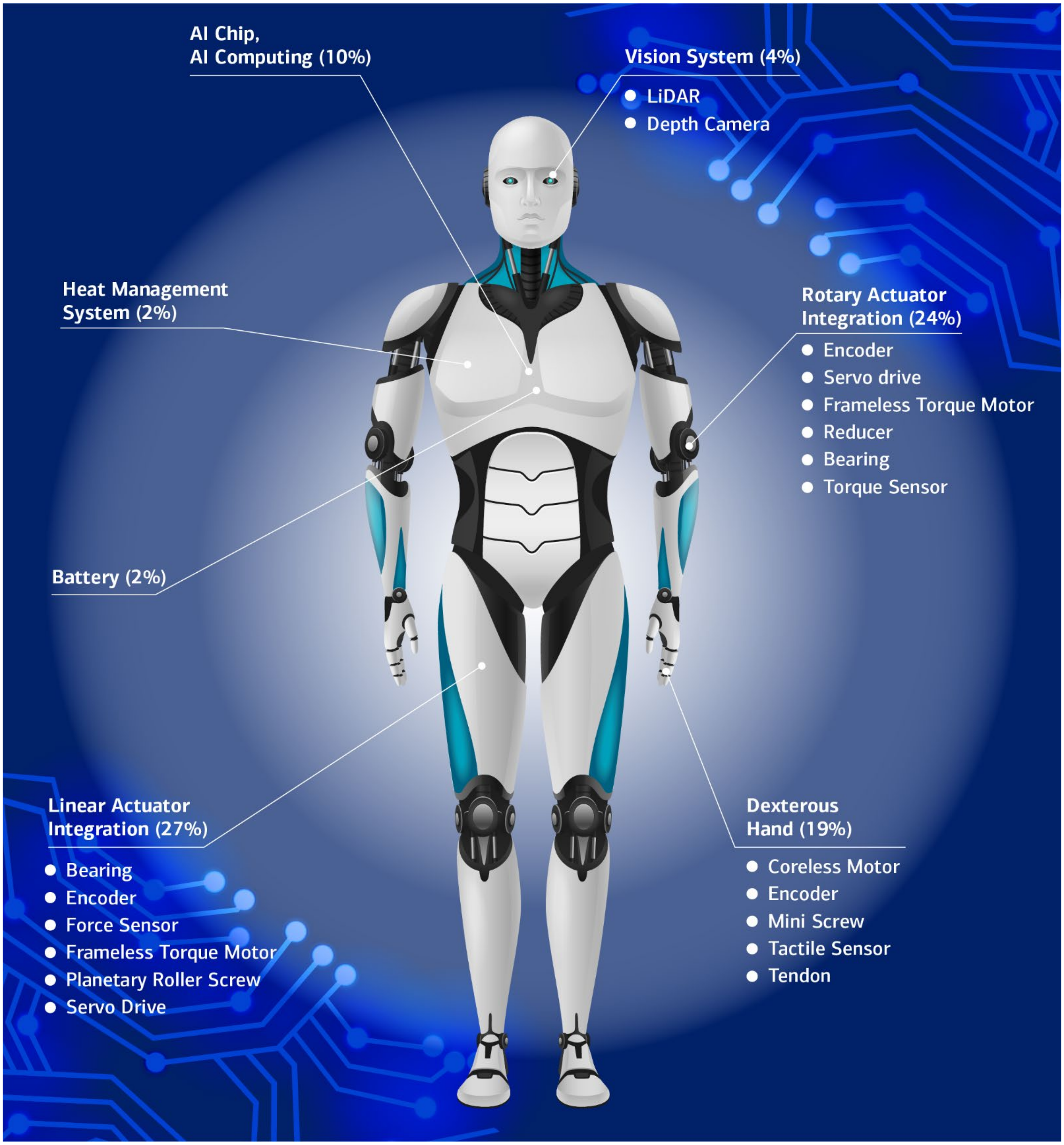
- **Force and torque sensors:** The force sensor measures the force or pressure applied to an object and converts it into an electrical signal to measure, control and monitor an actuator. It is mainly used in linear actuators. Meanwhile, the torque sensor measures the torque or rotational force applied to an object.

- **Inertial measurement units (IMU):** IMUs are used in humanoid robots to measure the robot's acceleration, angular velocity and other motion parameters, which help the robot to perceive its own posture and motion state and maintain body balance. Apart from humanoid robots, IMUs are also used in consumer electronics, auto and aerospace sector.

- **Tactile sensors:** Tactile sensors are usually used on the dexterous hands of humanoid robots (usually 10 units per robot, one on each finger), measuring the force and pressure applied between the sensor and an object. It mimics receptors in human fingers that would be a crucial part of human skin.

Exhibit 3: What components are used in humanoid robot manufacturing?

Infographic denoting the key components of a humanoid robot and estimated content value percentage of each



Source: BofA Global Research

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Robots: Still processing

Among all major humanoid robot components, BofA Global Research believes the AI chip, frameless torque motor, coreless motor and battery will have relatively higher certainty in technology routes. However, it's likely that the design or choice of other components will experience significant changes in the coming few years, given that the development of humanoid robots is still at a nascent stage. Potential changes mainly include:

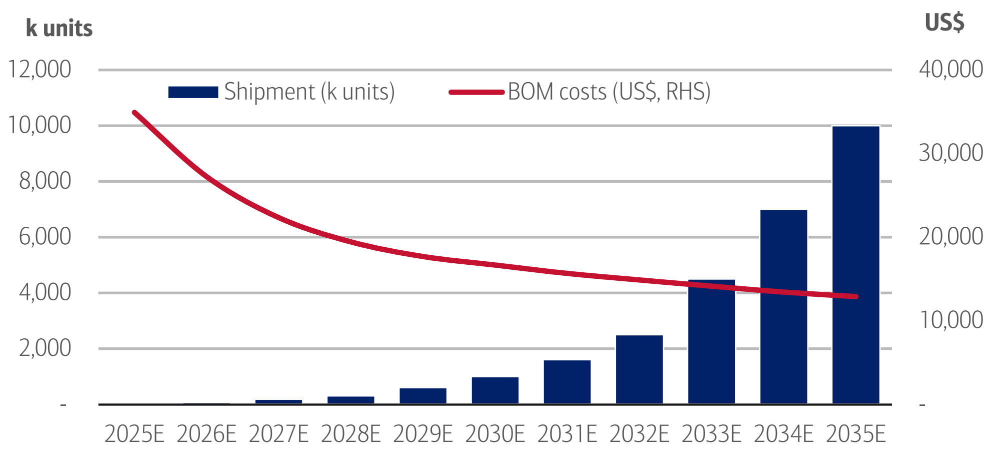
- **Use of linear actuator**: Some humanoid robot designs may adopt all-rotary actuator solutions, without using linear actuators. Moreover, there is potential that some humanoid robots may use ball screws to replace planetary roller screws in order to save costs.
- **Harmonic reducer vs. planetary reducer:** Planetary reducers generally have higher resistance to impacts and lower prices than harmonic reducers, so some humanoid robot companies could use planetary reducers to replace harmonic reducers in robot legs.
- **Design of dexterous hands:** The dexterous hand's design may undergo significant changes in the coming few years, including the number of DoFs, the design of transmission system, and the technology route for tactile sensor and electronic skin.
- **Use of sensor:** Sensor use may vary across different humanoid robot designs and desired functions. Notably, the penetration of 6D force and torque sensors could increase in the coming few years thanks to falling prices, which would support better sensory functions of humanoid robots.
- **Camera vs. LiDAR:** Some humanoid robots may adopt an all-camera design for the vision system while others may use a combination of depth cameras and LiDAR. Generally speaking, LiDAR performs better in long-distance measurement, has higher robustness against sunlight, and is usually used in outdoor scenarios.

From parts to price tags

It's important to note that humanoid robots are still not standard spec products, and as such it is difficult to predict their cost. In March 2025, BofA Global Research estimated the total bill of materials (BOM) cost (or hardware cost) of a typical humanoid robot should stand at around $35,000 per unit by the end of 2025 if most of the components are made in China. This is based on the assumption that: 1) a humanoid robot uses 16 rotary actuators and 14 linear actuators; 2) its rotary actuator uses harmonic reducers; 3) its linear actuator is based on planetary roller screw; 4) its dexterous hand has 6 degrees of freedom; 5) its vision system includes one depth camera and one LiDAR; and 6) the humanoid robot mainly uses Chinese-made components, if possible, in order to save costs.

Looking ahead, BofA Global Research expects the BOM cost of a humanoid robot to fall to $13,000-$17,000 per unit by 2030-2035, thanks to economy of scale and the improvement of component design (Exhibit 4). This corresponds to an over 50% decline in the BOM cost over the next five years, equivalent to a ~14% CAGR (compound annual growth rate) of decline.

Exhibit 4: Humanoid robot's BOM costs may fall below $17k by 2030, when annual shipments reach 1mn
Humanoid robot shipments vs. BOM costs (in China)



Source: BofA Global Research estimates

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The bot next door: Three billion by 2060

According to BofA Global Research, humanoid robots should see strong shipment growth in the coming decade driven by rising end-demand due to an aging population and labor shortages, improving technology (especially AI and motion control) and product design, falling BOM costs, and the expansion of end-applications.

BofA Global Research is optimistic for the long-term demand of humanoid robots as they commence massive adoption in household and service applications. In fact, BofA Global Research believes that global humanoid robot shipments will reach 18,000 units in 2025. And in 2030-35, they expect the annual shipment volume of humanoid robots to reach 1 million (vs. 400,000 units earlier)/10 million units globally, which corresponds to an 88% CAGR in 2025-35E.

However, there could be uncertainties to industry demand growth. For one, it still takes time for humanoid robot companies to optimize their product design and expand their end-application in the near term. Additionally, technological complexity and production costs remain high in the near term, and it's possible that there will be near-term production capacity constraints for key components, such as planetary roller screws.

However, despite potential challenges, BofA Global Research believes the adoption of humanoid robots will follow a three-stage development trajectory in the coming decade, starting from industrial and logistic applications, then on to business services, and finally to household use:

- **Stage 1 – Development (2025-27):** Humanoid robots will initially be used in small batches in well-structured or semi-structured environments, such as industrial production and logistics, where they will mainly be used for material handling, assembly, sorting and quality check tasks. This will help humanoid robots accumulate real-world data for further training and model calibration. Some humanoid robot companies have already started real-world application in over the past year.

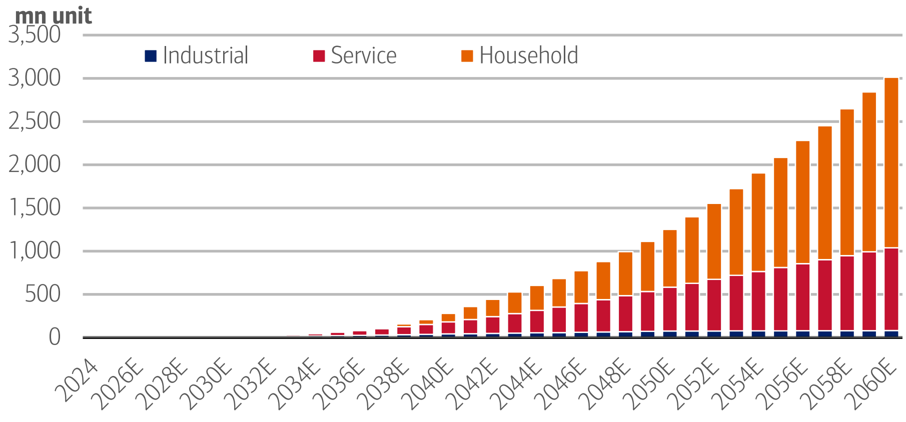
- **Stage 2 – Mass adoption for commercial use (2028-34):** After a few years of training in industrial and logistics applications, the design and control algorithm of humanoid robots would be significantly improved. Meanwhile, humanoid robots will be increasingly integrated with LLMs, which enables real-time interaction with humans. With improved design and functionality, humanoid robots will start to see massive adoption in commercial applications, including education and business services. They can also work in less-structured environments, such as flexible manufacturing and outdoor engineering, all of which will support shipments of over 1 million units annually.

- **Stage 3 – Mass adoption for all (2035 onwards):** Humanoid robots will achieve massive adoption for general purposes with highly unstructured working environments, such as in households and for elderly services. This is supported by well-developed functionalities with smooth interaction with humans, and affordable production costs. At this stage, annual shipments of humanoid robots could reach over 10 million units per year, thanks to a much larger user base.

In the long run, BofA Global Research expects the total units in ownership (UIO) for humanoid robots to reach three billion units globally by 2060E, assuming 1) humanoid robots can replace 20% of the workforce in the industrial sector, and 50% of the workforce in the service sector; 2) a humanoid robot can replace 2.5/1.5 workers in the industrial/service industry; and 3) the penetration of humanoid robots can reach ~0.7 units per household in the steady stage. This corresponds to approximately 0.3 units per capita, slightly higher than that of passenger vehicles (0.2 units currently), but lower than that of smartphones (0.9 units currently). And BofA Global Research expects the service/household/industrial sector to account for 65%/32%/3% respectively, of the end-application of humanoid robots at the steady stage (Exhibit 5).

Exhibit 5: Total units in ownership (UIO) could reach 3 billion by 2060E

Long-term forecast of humanoid robot UIO between industrial, service and household applications.



Source: BofA Global Research

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A bit of this, a byte of that...

What needs to happen to achieve mass adoption? Firstly, humanoid robot companies still need to overcome a series of key bottlenecks, including: 1) a strong AI system powered by LLM/VLM that enables real-time interactions with humans; 2) a robust motion control system (or "little brain") that supports complex motions; 3) sufficient real-world data to train the AI algorithm; 4) a sensory system that can generate accurate environmental information in complex and uncertain environments; 5) the deployment of computing power on the edge side; and 6) optimizing product design to make the robot more suitable for mass production with lower costs.

And there are risks to BofA Global Research's humanoid robot forecasts including regulation, chip supply and machine tool availability – all of which could lead to slower-than-expected development of humanoid robots in the coming decade. How?

- **Regulatory risk**: AI regulations on privacy and data security could affect the evolution of embodied AI. For example, the proposed European Union (EU) AI Act encompasses comprehensive rules for trustworthy AI. It bans certain applications that pose a threat to citizens' rights and democracy, e.g. emotion/facial recognition technology used for surveillance or law enforcement purposes.
- **Availability of processor chips**: A processor chip is the core of the "brain" of a humanoid robot, mainly used for model inference and computation. Currently, the humanoid robot processor chip market is dominated by US players, so any potential non-availability of high-performance processor chips may hinder Chinese humanoid robot companies' progress of mass production.
- **Availability of high-end machine tools**: Some precision parts of humanoid robots (such as planetary roller screws and harmonic reducers) require high-precision grinding tools for mass production, which are still dominated by a few European and Japanese companies. As such, the availability of high-end machine tools could potentially hinder the capacity expansion of humanoid robot components and impact the ramp-up trajectory of humanoid robots as a result. On the other hand, BofA Global Research believes the availability of critical materials, such as high-performance alloy steel and neodymium (NdFeB) magnets, will not become a bottleneck in the near term.

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Disclosures