ANDROID / ROBOTICS NEWS

Meet the Humaoid Android That's Changing Robotics – Clone Robotics

October 28, 2024

Clone Robotics has unveiled a pioneering humanoid torso that sets a new standard in robotics. This innovation centers on using artificial muscles to replicate human-like movements, marking a significant step forward in creating robots that move with natural fluidity and precision. By integrating advanced technologies, Clone Robotics is transforming the boundaries of realistic humanoid robotics.

This development offers **a glimpse into a fast-approaching world** where robots move with the grace and fluidity of a human dancer, making their motions so natural that you might mistake them for one of us. This isn't a scene from a sci-fi movie; it's the reality **Clone Robotics** is bringing to life with their latest creation—a humanoid torso equipped with artificial muscles.

Unlike traditional robots with rigid, mechanical movements, these innovations **mimic the subtlety and precision of human motion**, opening a realm of possibilities once thought out of reach. From assisting in delicate medical procedures to performing intricate assembly tasks, these robots are poised to redefine how we interact with technology.

Clone Robotics

Central to this development is the use of artificial muscles, a fantastic option in the field of robotics. Unlike traditional motors, these muscles provide biomimetic accuracy, allowing for smoother, more flexible movements. This level of finesse enables robots to perform tasks that were previously unattainable, making them ideal for applications ranging from advanced prosthetics to realistic animatronics. But the true potential lies in the future these innovations promise. As Clone Robotics continues pushing the boundaries of possibility, we stand on the brink of an era where robots not only work alongside us but do so with a human-like touch.

TL;DR Key Takeaways :

- Clone Robotics has developed a groundbreaking humanoid torso that uses artificial muscles to replicate human-like movements, setting a new standard in robotics.
- The artificial muscles replace traditional motors, allowing for smoother, more flexible movements and enhancing the robot's precision in task execution. This opens new possibilities in prosthetics and teleoperation.
- The humanoid torso features bimanual capabilities, enabling the simultaneous use of both arms, which significantly boosts the robot's functionality and allows it to perform complex tasks requiring coordination and dexterity.
- The robot's advanced joint design, including actuated elbows, a cervical spine, and anthropomorphic shoulders, offers a wide range of motion and contributes to the robot's realism, making it suitable for applications requiring precise and adaptable motion.
- Clone Robotics uses a sophisticated valve matrix system to manage the artificial muscles, reducing the need for bulky equipment and enhancing the robot's responsiveness and agility. The robot operates at a peak power of 200 watts and is powered by water, emphasizing energy efficiency and reducing environmental impact.

Artificial Muscles: The Core of Biomimetic Motion

At the heart of this breakthrough are artificial muscles, which replace conventional motors to deliver smoother, more flexible movements. Unlike traditional robotic systems, these muscles emulate human muscle function, allowing for nuanced and lifelike motion. This advancement not only enhances the robot’s precision in task execution but also opens up new possibilities in fields such as:

- Advanced prosthetics
- Teleoperation systems
- Human-robot interaction research
- Realistic animatronics for entertainment

The artificial muscles provide a level of **biomimetic accuracy** that was previously unattainable with traditional robotics, offering a more natural and intuitive interaction between humans and machines.

Bimanual Capabilities: Enhancing Functionality and Dexterity

The humanoid torso features sophisticated bimanual capabilities, allowing the simultaneous and coordinated use of both arms. This significantly expands the robot’s functionality, allowing it to perform complex tasks that require high levels of coordination and dexterity. The ability to effectively use both arms is crucial for achieving human-like performance in various scenarios, such as:

- Manipulating delicate objects
- Performing intricate assembly operations
- Assisting in medical procedures
- Conducting precise scientific experiments

This bimanual design brings the robot closer to replicating human capabilities, making it suitable for applications where two-handed operations are essential.

New Superintelligent Androids

Advanced Joint Design: Expanding Range of Motion

A standout feature of Clone Robotics’ android is its advanced joint design. Equipped with actuated elbows, a cervical spine, and anthropomorphic shoulders, it offers a range of motion that closely mimics human anatomy. This design not only enhances movement capabilities but also contributes to the robot’s overall realism.
The **biomechanical accuracy** of the joints allows for:

- More natural and fluid movements
- Increased adaptability to various tasks

- Better interaction with human environments
- Enhanced performance in teleoperation scenarios

The advanced joint system enables the robot to navigate complex environments and perform tasks with a level of agility previously unseen in humanoid robotics.

Valve Matrix System: Streamlining Control and Efficiency

To manage the artificial muscles effectively, Clone Robotics employs a sophisticated valve matrix system. This innovative approach reduces the need for bulky equipment, resulting in a more compact and efficient robot design. The valve matrix system offers several advantages:

- Enhanced responsiveness and agility
- Improved control over individual muscle groups
- Reduced overall weight and size of the robot
- Increased energy efficiency

By streamlining control, the valve matrix system further supports the robot's ability to produce human-like movements, making it more adaptable to various applications and environments.

Energy Efficiency and Environmental Considerations

Clone Robotics has placed a strong emphasis on energy efficiency in their android design. Operating at a peak power of just 200 watts and powered by water, the robot is both clean and safe to operate. This focus on energy efficiency offers several benefits:

- Reduced environmental impact
- Lower operational costs
- Increased runtime on portable power sources
- Safer operation in various settings

The use of water as a power source not only makes the robot more environmentally friendly but also opens up possibilities for its use in sensitive environments where traditional power sources might be problematic.

Future Applications and Ongoing Development

The potential applications for Clone Robotics' technology are extensive and diverse. From advanced prosthetic limbs with enhanced functionality to sophisticated teleoperation systems requiring precise control, the possibilities are far-reaching. The company is also exploring the development of musculoskeletal superintelligent androids, aiming to expand the range of tasks these robots can perform.

As the technology continues to evolve, we can expect to see advancements in areas such as:

- More realistic and responsive robotic hands
- Full-body humanoid robots with enhanced mobility
- Integration of artificial intelligence for autonomous operation
- Improved human-robot collaboration in various industries

Clone Robotics' humanoid torso represents a significant leap forward in the field of humanoid robotics. By using artificial muscles and innovative control systems, the company is paving the way for more realistic and capable robots that can seamlessly integrate into various aspects of human life. As research and development in this area continue, we can anticipate even more exciting innovations that will further blur the line between human and machine capabilities.

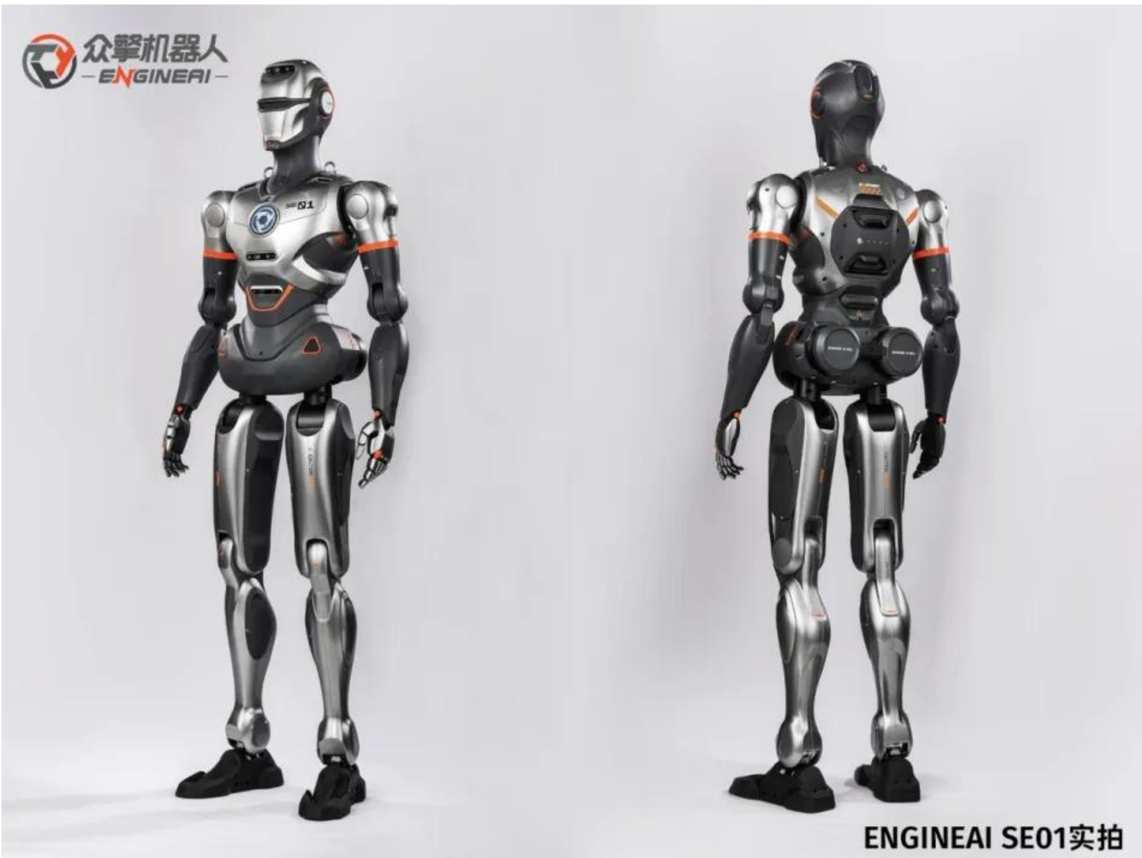
Meet EngineAI All-new Robotics SE01, Successfully Overcomes the Challenge of Natural Gait in Humanoid Robots for the First Time

ENGINEAI ROBOTICS TECHNOLOGY
October 25, 2024

ENGINEAI ROBOTICS TECHNOLOGY

Shenzhen, China, Oct. 25, 2024 (GLOBE NEWSWIRE) -- On October 24, 2024, Shenzhen EngineAI Robotics grandly launched its first full-size humanoid robot, SE01, worldwide. With its unique technological innovations and design aesthetics, it has redefined the standards in the field of humanoid robotics, sparking widespread industry discussion about new possibilities in future human-machine interaction.

One of the standout features of the SE01 is its cutting-edge end-to-end neural network solution. This technological breakthrough has conquered the long-standing challenge in the development of humanoid robots—natural gait. This allows SE01 to exhibit unprecedented elegance and energy efficiency in both stationary and dynamic states, significantly narrowing the behavioral gap between robots and humans. It completely overturns the stereotype of robots taking “choppy steps, bent knees, and stomping,” enabling the robot to walk with smooth, swift, and fluid strides.



SE01’s outstanding gait performance is attributed to EngineAI team’s exquisite technology and meticulous product design. The team independently developed an integrated harmonic joint module and significantly enhanced the robot’s flexibility and intelligence by combining reinforcement learning and imitation learning in its motion control solutions. This enables SE01 to achieve a natural, human-like gait, marking a new milestone in the evolution of machine intelligence.

In terms of hardware configuration, SE01 is equipped with dual processors from NVIDIA and Intel, as well as three sets of high-precision stereo cameras, forming an advanced visual neural network system. The collaboration of these cutting-edge devices gives SE01 excellent visual perception and analysis capabilities in complex environments. Coupled with its high-performance processing chips, SE01 is not only suitable for research and education fields but also performs well in complex industrial scenarios.

In product design, SE01 uses aerospace-grade aluminum alloy, making the body both sturdy and lightweight, and significantly enhancing the mechanical structure's lifespan. Additionally, the team achieved smooth and natural movement without relying on traditional six-dimensional force sensors and planetary roller screw actuators. This design significantly increases the product's reliability while controlling costs.

EngineAI Robotics' founder and CEO, Zhao Tongyang, pointed out that the launch of SE01 is not only a major technological advancement but also represents a fusion of technology and art. He stated, "Our goal is to make robotics technology truly serve humanity, and through continuous deepening of technological innovation and market expansion, we aim to bring embodied intelligent robots into every aspect of life."

Alpha: Water-powered humanoid robot with synthetic organs, muscles unveiled

Alpha: Water-powered humanoid robot with synthetic organs, muscles unveiled

Striving to stand out in the competitive humanoid robotics market, Polish-frim Clone Robotics has unveiled its first full-scale humanoid robot, Clone Alpha.

The humanoid integrates synthetic organs and artificial muscles, replicating skeletal, muscular, vascular, and nervous functions.

Clone's muscular system uses Myofiber, an artificial muscle technology introduced by the firm in 2021, to move its skeleton. It works by attaching muscles to precise points on the bones, just like in real animals.

Clone Robotics is now accepting preorders for the first 279 units of its humanoid robot, Clone Alpha.

Last month, the company revealed its latest innovation: a humanoid torso with human-like movements.

Biomimetic robotics

While companies like Tesla develop bots for household tasks, Clone Robotics focuses on biomimetic robotics. Founded in 2021, it aims to replicate the strength and dexterity of biological beings, tackling the complex challenge of mimicking the human body

The firm started by creating a robotic hand with artificial bones and muscles, designed to mimic human functionality. Its thumb rotates and can even catch a ball with ease. Building on this, the company developed a humanoid torso with lifelike features, including a movable elbow, cervical spine, and realistic shoulder joints.

Rather than designing movements around its robotic structure, Clone first replicated human anatomy and then enabled natural motion using artificial muscles. The result is strikingly realistic—almost uncanny in its resemblance to the human body.

Building on its expertise, Clone Robotics has now developed a humanoid designed to walk naturally. This is achieved through Clone's move from rigid actuators to soft, water-powered artificial muscles, aiming for more human-like movement.

Advanced artificial muscles

Clone Robotics plans to advance humanoid robotics with its artificial muscle technology, Myofiber. It animates the skeleton by attaching musculotendon units to anatomically precise points on the bones.

These monolithic units eliminate tendon failures and mimic the desirable traits of mammalian skeletal muscles, such as a response time under 50ms, over 30 percent unloaded contraction, and at least 2.2 pounds (1 kilogram) of contraction force for a 3-gram muscle fiber.

According to the firm, Myofiber is the only artificial muscle capable of achieving such power, speed, and efficiency.

The Clone's skeleton includes all 206 bones of the human body, with minor bone fusions, and features fully articulated joints, artificial ligaments, and connective tissues.

With precise ligament and tendon placement, the android achieves 164 degrees of freedom in its upper torso, including the shoulder with 20 degrees of freedom, the spine with 6 degrees per vertebra, and 26 degrees in the hand, wrist, and elbow.

The nervous system allows instantaneous control over the muscles with proprioceptive and visual feedback. The Clone is equipped with 4 depth cameras, 70 inertial sensors for joint-level feedback, and 320 pressure sensors for muscle force feedback. These are linked to microcontrollers that send data to the NVIDIA Jetson Thor GPU running Clone's Cybernet model.

The Clone's vascular system is powered by a compact, 500-watt electric pump resembling the human heart, delivering 40 SLPM at 100 psi. Its Aquajet valve technology operates under 1 watt of power, providing efficient hydraulic pressure to the muscles in a miniaturized design.

Impressive as it may seem on paper, Clone Robotics has yet to demonstrate a fully functional Alpha robot. While components show promise, successfully scaling from prototypes to complete humanoids will be a key test of their biomimetic approach.

NEO

Excels in industrial tasks

NEO is a humanoid with a wide range of capabilities. It excels in industrial tasks in sectors like security, logistics, manufacturing, operating machinery, and handling complex tasks. In the long term, we envision NEO providing valuable home assistance and performing chores like cleaning or organizing.

Muscle-like anatomy, can run, jog

If support is needed, a remote human operator can quickly take over NEO's vision and movement. NEO's body is engineered with muscle-like anatomy instead of rigid hydraulics, so it's strong and gentle like humans. NEO can walk, jog, climb stairs, and navigate your space naturally. As they move and perform tasks, they get even more efficient.

Helping the robotics community

1X is investigating how NEO can support individuals with mobility challenges by fetching items and providing companionship. NEO's potential extends to research, helping the robotics community explore fields like psychology and artificial intelligence. With NEO's continuous evolution, the possibilities for assistance, productivity, and learning are boundless.

High load carrying capacity

NEO is 5.41 feet long, and it weighs 66 pounds. The walk speed of the robot is 2.5 miles/hour with a 7.5 miles/hour run speed. It has a 44-pound carry capacity with a 2-4 hour run time. NEO is designed to be an all-purpose humanoid assistant to your daily life. That means NEO can take on many common tasks, whether helping you around the house, completing chores, or running errands.

Modeled after a human

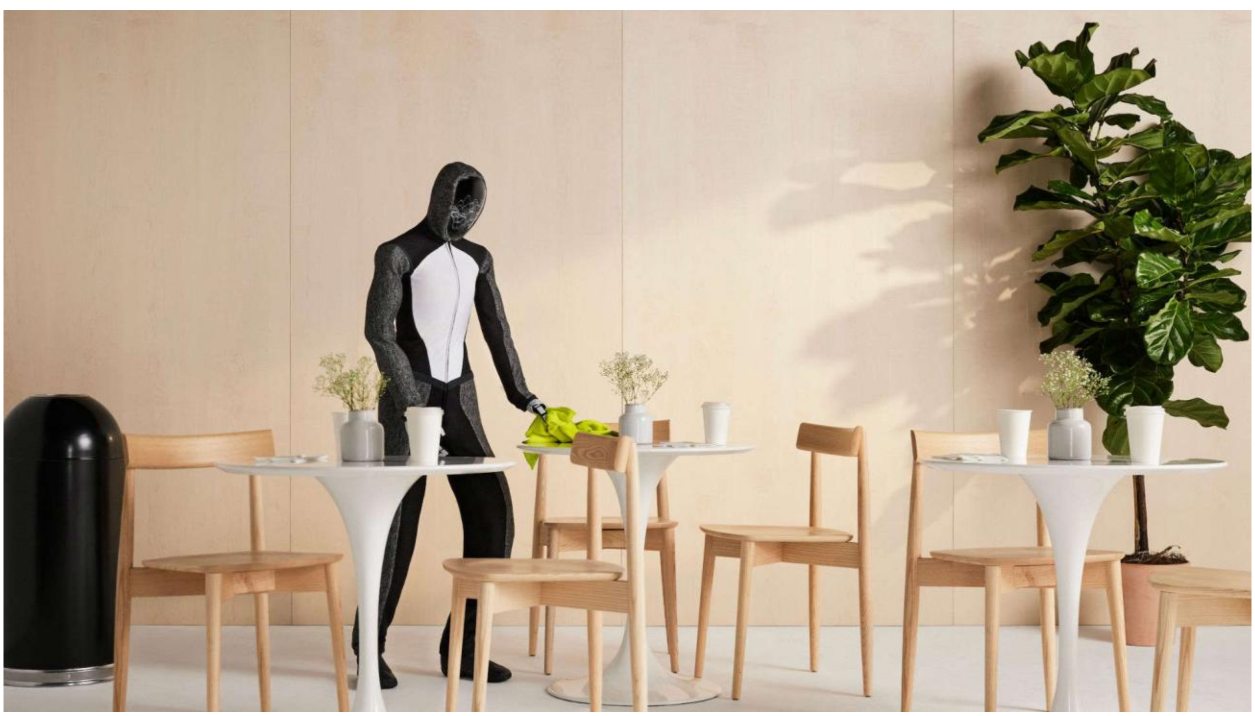
Humanoids are made to look like humans for different reasons. Firstly, humans are flexible and can move around in various ways. By copying the shape and movements, 1X's robots can do complex tasks and get around easily. Secondly, humans are good at understanding each other without words, like using expressions and gestures. When robots look like humans, they can use these familiar ways to communicate and work with humans.

Powered with AI

Using embodied artificial intelligence, NEO will understand its environment deeply, thanks to the fusion of its AI "senses" and physical body. NEO continuously learns and improves, becoming smarter and more capable over time.

Human-android interaction

The more humans interact within themselves, the more natural and intuitive navigating life with NEO will feel. NEO will understand their own environment and how to handle fragile items, creating seamless collaboration and immersive human-android interaction.



Humanoid robots have long been a staple of science fiction, but there is now real progress being made. A range of new models made by or backed by the likes of Boston Dynamics, Tesla and OpenAI are able to walk and move like humans, as well as perform feats of agility and dexterity.
But it's the ability to incorporate artificial intelligence (AI) into these humanoid robots that could truly allow them to make the leap into everyday life. AI-enabled "brains" could help dramatically improve the ways that humanoid robots interact with humans and the outside world. This would give humanoid robots their "iPhone moment," meaning they break through into the market in a big way.

Large language models, the technology behind AI chatbots like OpenAI's ChatGPT, have shown they are good at learning from the vast amounts of data they are fed with and are good at selecting the right information and using it to reason with. They are the key to something called "embodied intelligence."

Embodied intelligence refers to the integration of cognitive processes with physical actions, a bit like how our brains control our limbs. The aim of embodied intelligence is to enable robots to interact with the world in a similar manner to humans. This concept relies on large language models and visual AI systems to help computers make sense of objects in videos and pictures.

It establishes a machine logic about the relationships between the observer and the objects, and helps the robot understand how interactions could happen between them. LLMs alone wouldn't be acting as the robot's "brain" necessarily, but the technology could help improve how they generally interact with the world.

A good example is an AI system built by Google called PaLM-E. Engineers behind the development of PaLM-E trained it to directly ingest raw streams of robot sensor data. The resulting AI system allowed the robot to learn very effectively.

This field is advancing so quickly that by the time I finish writing this article, a new, innovative AI model or paradigm may be released. Advancements such as PaLM-E infuse humanoids with visual-spatial intelligence, allowing them to make sense of our world without requiring extensive programming.

From factories to homes

The potential applications of humanoid robots are vast and varied. Early modern research in humanoid robotics focused on developing robots to operate in extreme environments that are dangerous and difficult for human operators to access. These include Nasa's Valkyrie robot, designed for space exploration. However, we will probably first see commercial humanoid robots deployed in controlled environments such as manufacturing.

Robots such as Tesla's Optimus could revolutionize manufacturing and logistics by performing tasks that require precision and endurance. They could work alongside human employees, enhancing productivity and safety.

For example, in a factory, Optimus could handle hazardous materials, perform quality control inspections, and assist in assembly processes. The new Boston Dynamics Atlas2, announced a few months ago, already demonstrates some use cases for use in factories, such as lifting and storing heavy components.

Beyond industrial applications, humanoid robots could also find a place in households. Imagine a future where Optimus helps with daily chores, such as cleaning, cooking, and even caring for the elderly.

Earlier this year, Stanford University's Aloha robot went viral on the internet for demonstrating its ability to make Chinese food, load dishes into a dishwasher, prepare beds, and put laundry into the wardrobe on its own. Eventually, we may see humanoids deployed in more professional areas such as hospitals for care roles or in public security, requiring professional domain knowledge and high public acceptance.

Market viability

While the technological potential of humanoid robots is undeniable, the market viability of such products remains uncertain. Several factors will influence their acceptance and success, including cost, reliability, and public perception.

Historically, the adoption of new technologies often faces hurdles related to consumer trust and affordability. For Tesla's Optimus to succeed commercially, it must not only prove its technical capabilities but also demonstrate tangible benefits that outweigh its costs.

There are ethical considerations too. For instance, who has access to all the data collected by the robot as they interact with humans, sometimes in what could be deeply private moments? There is also the potential for humanoid robots to displace jobs, such as in the elderly care sector where they could have a key role.

These ethical factors will play a critical role in shaping public opinion and regulatory frameworks. Science fiction author Isaac Asimov drafted Three Laws of Robotics for humans to interact with robots effectively. In abridged form, they stipulate that a robot may not injure a human being, that a robot must obey orders given it by human beings and that a robot must protect its own existence as long this doesn't clash with the first or second law.

These laws may still be relevant, as current debates extend beyond just humanoid robots to include any high-level autonomous systems that could pose societal risks and cybersecurity issues.

But it's important to remember that current AI is still far from the real intelligence we are familiar with, so the scenarios depicted in movies like "AI: Artificial Intelligence," directed by Steven Spielberg, or "I, Robot," starring Will Smith, are unlikely to happen anytime soon.

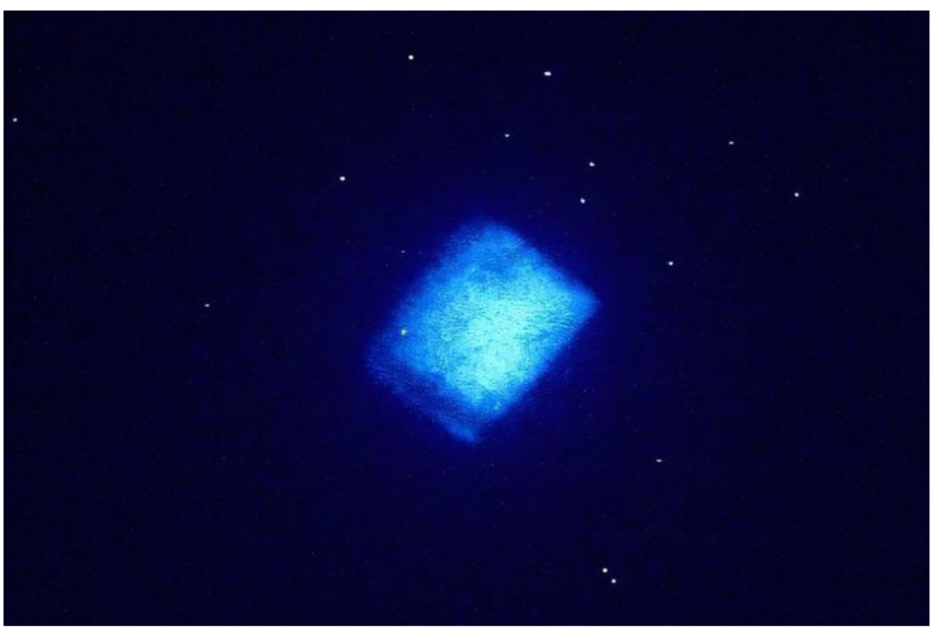
We need experts from various fields, including robotics, ethics and economics, to weigh in on the development of humanoid robots. Their insights will be crucial in navigating the challenges and opportunities presented by the technology.

As we stand on the brink of this new technological frontier, it is essential to consider not only what is possible but also what is desirable for our collective future. Meanwhile, as I watch my garden's grass grow steadily upwards, all I can think about is having a humanoid robot trim it—after it has made me a relaxing cup of tea.


AI could be the breakthrough that allows humanoid robots to jump from science fiction to reality© PsyPost

IMMORTAL ANDROID POWERED BY A DIAMOND GRAPHITE BATTERY?

Scientists produce world's first carbon-14 diamond battery with potential lifespan of thousands of years



Diamond battery sample. Credit: University of Bristol

Scientists and engineers from the University of Bristol and the UK Atomic Energy Authority (UKAEA) have successfully created the world's first carbon-14 diamond battery.

This new type of battery has the potential to power devices for thousands of years, making it an incredibly long-lasting energy source. The battery leverages the radioactive isotope, carbon-14, known for its use in radiocarbon dating, to produce a diamond battery.

Several game-changing applications are possible. Bio-compatible diamond batteries can be used in medical devices such as ocular implants, hearing aids, and pacemakers, minimizing the need for replacements and distress to patients.

Diamond batteries could also be used in extreme environments—both in space and on earth—where it is not practical to replace conventional batteries. The batteries could power active radio frequency (RF) tags where there is a need to identify and track devices either on Earth or in space, such as spacecraft or payloads, for decades at a time, thus reducing costs and extending operational lifespan.

Professor Tom Scott, Professor in Materials at the University of Bristol, said, "Our micropower technology can support a whole range of important applications from space technologies and security devices through to medical implants. We're excited to be able to explore all of these possibilities, working with partners in industry and research, over the next few years."

The carbon-14 diamond battery works by using the radioactive decay of carbon-14, which has a half-life of 5,700 years, to generate low levels of power. It functions similarly to solar panels, which convert light into electricity, but instead of using light particles (photons), they capture fast-moving electrons from within the diamond structure.

"Diamond batteries offer a safe, sustainable way to provide continuous microwatt levels of power. They are an emerging technology that use a manufactured diamond to safely encase small amounts of carbon-14," said Sarah Clark, Director of Tritium Fuel Cycle at UKAEA.

A team of scientists and engineers from both organizations worked together to build a plasma deposition rig, a specialized apparatus used for growing the diamond at UKAEA's Culham Campus.

This development is the result, in part, of UKAEA's work on fusion energy. The expertise gained in fusion research is helping to accelerate innovation in related technologies.

Provided by University of Bristol

Revolutionary Diamond Batteries Turn Nuclear Waste into Millennia-Lasting Power

Researchers have developed a groundbreaking battery using radioactive diamond technology that can generate electricity for thousands of years. By repurposing radioactive waste, this innovative energy source offers consistent power over millennia with minimal environmental impact. Though it produces only small amounts of energy, its durability and potential applications make it revolutionary.

Nuclear reactors use graphite, a form of carbon, to regulate radioactive reactions. During this process, some of the graphite becomes radioactive and contains carbon-14, a waste product that usually requires long-term storage. In diamond battery production, the carbon-14 is extracted by heating the graphite, releasing it as a gas. This gas is then converted into artificial diamonds under high pressure and temperature, creating a material capable of generating electricity through beta radiation.

Safety Features and Radiation Shielding

Despite its use of radioactive material, the diamond battery is designed with built-in safety measures. The outer layer of the battery consists of a non-radioactive diamond shell, which effectively blocks harmful radiation. Since carbon-14 emits only beta radiation, this shielding ensures that the battery is completely safe for use in everyday applications. The continuous emission of radiation within the diamond generates a steady electric current, making it an ideal long-term power source.

Promising Applications for Long-Term Power

While the energy output of diamond batteries is small—roughly 15 joules per day for one gram of carbon-14—it is sufficient for many specialized uses. These batteries could power medical implants such as pacemakers and hearing aids, eliminating the need for replacements. In space exploration, they could provide reliable energy for satellites, drones, and probes operating in remote environments for decades without maintenance. With over 95,000 tons of radioactive graphite waste in the UK alone, there is no shortage of raw material for production.

A Step Toward Sustainable Energy

Diamond batteries represent a breakthrough in sustainable energy technology, turning nuclear waste into a practical power source. The potential for these batteries to last thousands of years, as claimed by California-based company NDB, highlights their long-term reliability. This innovation could pave the way for more sustainable solutions in fields ranging from medicine to aerospace.

Diamond batteries offer an innovative way to repurpose nuclear waste into a reliable, long-term energy source. Their potential to power medical devices, space technology, and more highlights their versatility despite low-energy output. This breakthrough underscores the importance of sustainable energy solutions for addressing global challenges.

28,000 Year Nuclear Waste Battery? Diamond Batteries Explained

Given the relatively short lifespan, overheating, and battery cell supply issues of current battery technologies, they can't be used everywhere. Take satellites, high-altitude drones, healthcare, or even spacecraft, all of which require energy storage with a very long life. But some companies are claiming that diamond battery technology can kill two birds with one stone: creating energy storage that could last for thousands of years by putting nuclear waste to use… potentially powering everything from EVs to cellphones. Is this the holy grail of battery technology or hype; and more importantly, is it safe? Let's explore Nano Diamond Batteries and where this might be going.

Modern life relies on mobile battery-powered devices: at work, at home, at school, and while traveling. We need batteries for communication, transportation, storing energy from renewables like solar and wind, you name it … and it's undeniable that lithium-ion batteries have opened up a world of possibilities.

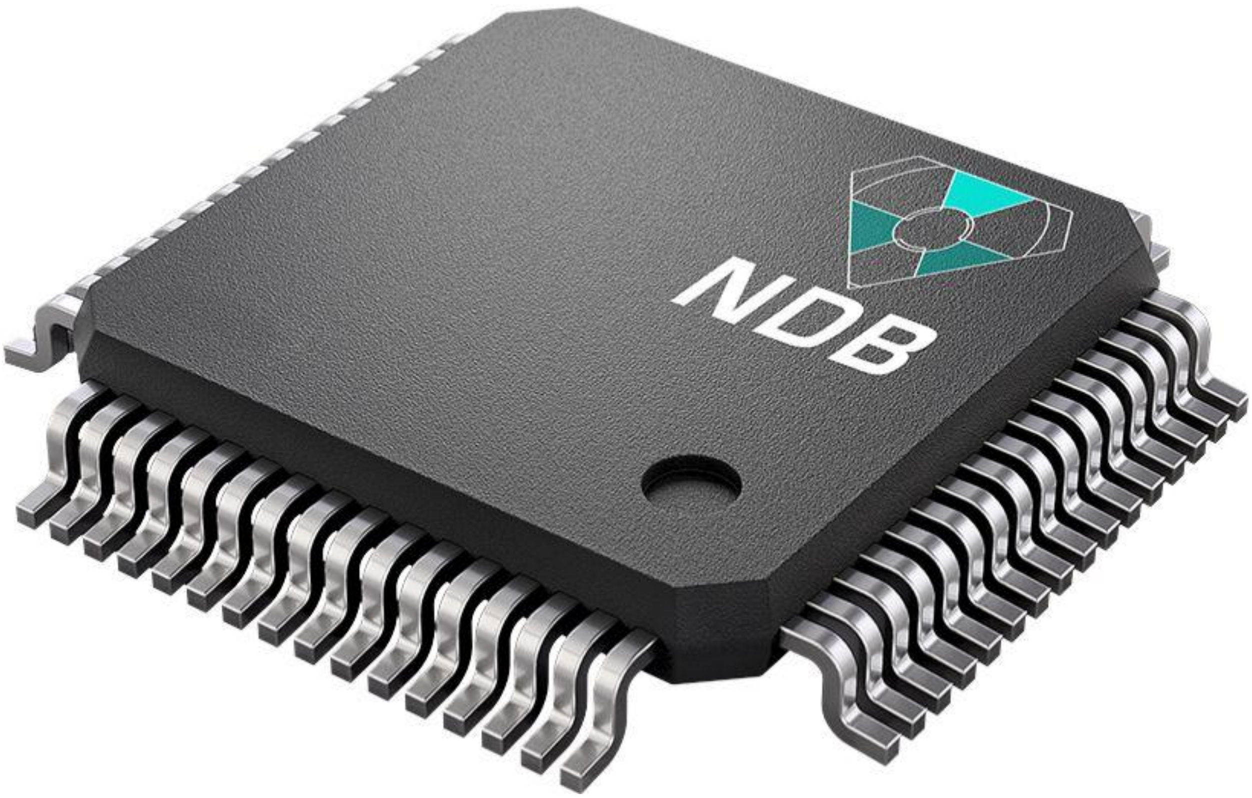
Even though we've seen significant progress with the lithium technology over the past few decades, challenges such as overheating, expensive casings, short lifespan, and underperformance in extreme temperatures still need to be overcome. So the quest for the holy grail of batteries continues.

Aiming to reach carbon neutrality in the next few decades, batteries and renewable power sources need to evolve alongside each other to solve this puzzle. The International Renewable Energy Agency (IRENA) estimates that stationary battery storage will grow from only 2 gigawatts (GW) worldwide in 2017 to around 175 GW in 2030. But batteries aren't the only way to compensate for the intermittent operation of solar and wind. We also have nuclear power. [1]

Nuclear accounted for 10.3% of the world's electricity generation in 2019. [2] It's widely considered to be a stable, carbon-friendly energy source that can be used to support the intermittency of other renewables. But besides being expensive and having long construction times, the unresolved problem of what to do with long-lived radioactive waste is crucial for its development. There's a lot of "not in my backyard" to that debate. If you're interested, I have an episode on Small Modular Reactors that gets into the future of nuclear power. As of today in the U.S., there are 96 commercial nuclear power reactors currently operating, and more than 90,000 metric tons of highly radioactive nuclear waste, including spent fuel and other material. [3]

Pulling together the challenges of conventional batteries and the problems derived from nuclear waste, a new technology called Nano Diamond Battery Technology is being touted as an energy-disruptive innovation.

NDB, a California-based start-up made headlines when it announced that it completed two proof-of-concept tests of its nano diamond battery, made from nuclear waste encased in artificial diamond. But the root of this energy storage technology is known as betavolatics, which is powered by beta decay and goes back to the 1950s.



In 1953, Paul Rappaport proposed the use of semiconductor materials to turn the energy from beta decay into electricity. Unlike common electricity-generation technologies that utilize hydro or wind turbines to spin copper coils within magnets to produce an electric current, betavoltaic devices can generate current when placed close to a radioactive source.

Imagine placing a semiconductor material, like Silicon, in a box with Strontium-90, which is a radioisotope produced from nuclear fission. It has a half-life of almost 30 years.[4] A semiconductor material, like Silicon, can both act as an isolator or conductor depending on the conditions it's subjected to, like temperature, light, or electric current. It's actually very similar to how solar cells work when collecting solar radiation. In this case, the radioactive element emits beta particles that separate electron and hole pairs in the semiconductor (holes collect on the positive side and electrons collect on the negative side). Bridging the two sides allows the electrons and holes to find each other resulting in an electric current … in short, this turns radiation into electricity. [5] [6]

Using this principle, in 2016, researchers from the University of Bristol unveiled the world's first known diamond nuclear battery, which is based on this betavoltaic concept. Tom Scott, Professor in Materials at the University of Bristol, described the advantages as the emission free, long-term production of clean energy from nuclear waste.[7] [8]

A great portion of nuclear waste is graphite, which is used as a moderator and reflector in a nuclear reactor. The graphite becomes radioactive over time because of its exposure to radiation. And depending on the reactor type, the graphite blocks can be extremely large and heavy, as well as irradiated with long-lived radioisotopes, which makes graphite expensive and tricky to dispose of or recycle.[9]

The reason why graphite is important here is that radioactive graphite contains Carbon-14 (C-14), which turns into harmless Nitrogen-14, an anti-neutrino, and an energetic electron — aka a beta-decay electron. But that's already TMI … I'm not going to turn this into a chemistry class. I'd probably flunk it.

The idea behind the research from the University of Bristol is to manufacture batteries that can harness this by-product of C-14 as energy. In its gas form at low pressure and elevated temperatures, you can convert it into a radioactive diamond. Then for safety you encapsulate it again in a non-radioactive diamond layer. So it's a radioactive diamond … in a diamond. Even though the researchers say that only a small level of radioactivity is detected near their diamond, would you really want to use a nuclear powered pacemaker inside your body? [10] [11] Actually … there were Plutonium powered pacemakers, but that's a different video.[12]

Even though we typically equate nuclear power to great amounts of energy being produced, these betavoltaic batteries can only generate power in the range of microwatts, which is why headlines and press releases about NDB batteries have been overselling it. This is not the future of electric vehicles. If their breakthrough proves to be true, it has some potential … for very targeted scenarios.

The difference between the batteries from Bristol to NDB's is in the layers of the encasing diamond. While the researchers of Bristol used only a diamond layer to protect the radioactive diamond, NDB combines multiple layers of paneled nano diamonds to protect the core. These micro-sized single crystal diamonds are very good at conducting heat, so they move heat away from the radioactive isotope materials so quickly that the transaction generates electricity.[13] [8]

There are several concepts to ensure safety, but there's still a lot of questions around this since we haven't seen any test results from the company yet. But a couple of those things are the diamond encapsulator, which is the most thermally conductive and hardest material available, in addition to containing the radiation within the device.

Next up is the Lock-in System, which helps to prevent proliferation of dangerous nuclear isotopes like Pu-238 and U-232. According to NDB, their battery uses an ion implantation mechanism that prevents it being used for purposes other than power generation. [14] [15]

Besides these safety claims, the company says its technology has a maximum lifespan of 28,000 years and could one day become a source of low-carbon power for anything that needs it – from Evs to smartphones. Although this technology looks awesome, it's still highly questionable since the power coming from betavoltaics is so low. Remember, microwatts low.

According to a report, the proof-of-concept design was evaluated by the Lawrence Livermore National Laboratory, which reported a 40% charge improvement in efficiency over a standard diamond. But I couldn't find any information on how Lawrence Livermore National Laboratory tested the proof-of-concept.

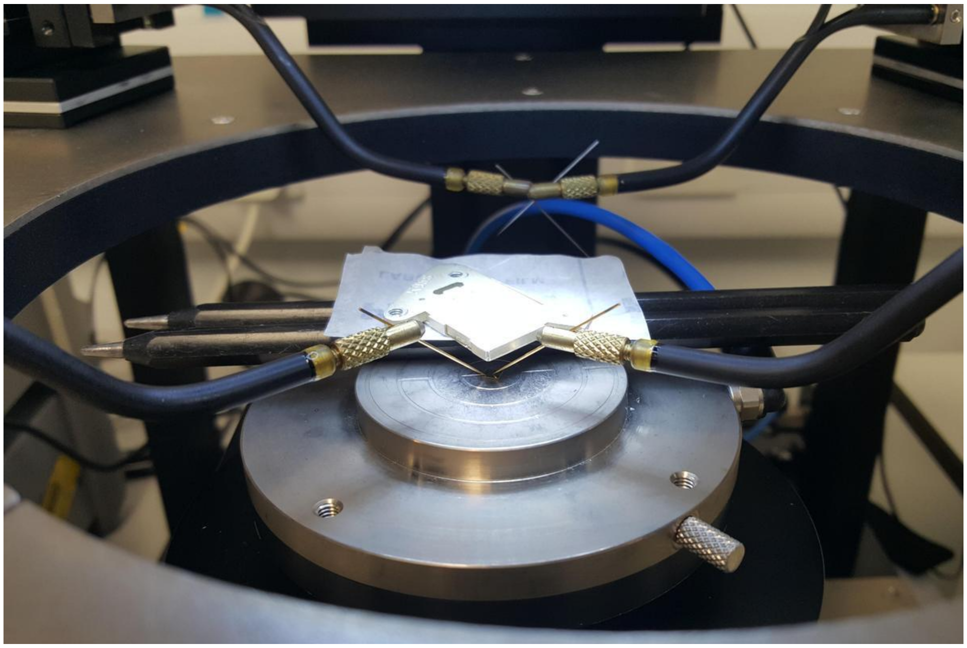
Most of the claims have no hard evidence or proof yet, other than what NDB has reported. NDB doesn't fully explain what happens to the heat it generates during energy conversion other than to describe thermal vents to dissipate heat. [16]

The company mentions several possible applications in their website like consumer electronics, automotive, medical devices, aerospace, but we still don't have precise specifications. Yet, an image of the battery shows a power level of 100 microwatts.[17] It's important to drive that point home. It's highly unlikely to power an electric vehicle, let alone an iPhone at microwatt scale. But, it doesn't mean the tech doesn't work for more appropriate applications. If enough of these battery cells were combined, they could power small LED displays or devices that require low power, like medical or communication devices … think internet of things (IOT) and pacemakers. But powering Evs that demand an insane amount energy is where media coverage went a little overboard.

So back in the land of reality where do the benefits of this technology make the most sense? And is there a market for it?

Well, the company hopes to start selling the battery to commercial partners, including space agencies for long duration missions by 2023. [18]

In addition, NDB isn't alone in nuclear diamond battery game. The scientists at Bristol saw a great opportunity in extracting and repurposing nuclear waste material, but without overselling it. They spun off Arkenlight, a company formed to take on the commercialization of their diamond battery concept. [19]



Morgan Boardman, the new company's CEO says:

"…It is a very novel approach, which we find that people like because it's sort of a cosmic rag-and-bone man narrative…" -Morgan Boardman

He also points out that the technology can help with the carbon emissions challenge:

"…With the resources used to manufacture, say, an AAA battery, we would offset nearly 2.5kg of carbon in the manufacture of an equivalent energy density of diamond batteries…" -Morgan Boardman

Unlike NDB, Arkenlight doesn't claim that their batteries will power cars or even laptops. That's because they provide thousands of times less power than a conventional AA battery – although they will last thousands of times longer. Arkenlight's power cells would take about 5,000 years to reach 50% discharge. The company sees their batteries powering small detectors, wireless IoT devices/sensors or medical implants. [19]

It can be mechanically stacked in series or parallel for greater power, and can be paired with capacitors for intermittent high power use cases. [20] [21]

In 2018, Bristol researchers did an interesting experiment to test out the strength and durability of their diamond batteries, placing them at the top of a volcano. In the experiment, a prototype of Arkenlight betavoltaics was used to power sensors inside a remote-monitoring station, known as a ‘dragon egg.’ The eggs were designed to be placed on an active volcano by drone in order to measure humidity, vibrations, and the emissions of toxic gases. They could remain in service for months without depleting their energy. [22]

Arkenlight aims to establish a factory at one of the several decommissioned nuclear power plants in the South West of England, or possibly North Wales. That way, the company has easy access to carbon-14 isotopes for battery manufacturing. Boardman estimates that their carbon-14 batteries will begin appearing in devices around 2024 if everything goes well. [19]

In terms of challenges, the use of radioactive material complicates matters, so manufacturing them involves a significant amount of care and safety procedures you wouldn’t have with a typical chemical battery. While the process is made safe, the safety infrastructure required to produce it, and governmental permissions, come with big costs.

Even though the researchers from both Bristol University and NDB claim that nuclear batteries have small or no radioactivity level due to the diamond containment, I’m not sure if I’d feel comfortable having a nuclear powered cellphone even if it was possible at this point. Putting aside the overhyped headlines, there’s still some interesting promise and use cases for diamond batteries … even though they’re still in their theoretical phase. We’re going to need to wait a few more years until NDB and Arkenlight have some real prototypes and solid results to call this one. Not every battery technology has to be a lithium ion killer. It’s okay to have an exciting breakthrough for a very targeted market, which is what this is.

World's First 5,700-Year-Lifespan Nuclear Diamond Battery Revealed by UK Researchers

The carbon-14 diamond battery generates electricity using the energy released by the radioactive decay of carbon-14. This is a substance usually used in carbon dating. It is enclosed inside a diamond, which is among the most durable materials on the planet. This safely contains the radiation while producing power. Carbon-14 releases short-range radiation, which gets absorbed by the diamond shell, assuring safety while producing small amounts of electricity. This groundbreaking battery functions in a similar manner to solar panels, except instead of converting light into power, it uses fast-moving electrons resulting from radioactive decay.

The end result of this process is a long-lasting, dependable source of energy with a phenomenal lifespan. Because carbon-14 has a half-life of 5,700 years, the battery continues to retain half of its capacity even after thousands of years. Diamond batteries provide a secure and environmentally friendly way to deliver steady microwatt levels of power.

Potential Applications of the Diamond Battery

Among the most exciting characteristics of carbon-14 diamond batteries is their adaptability. They can be used for a large number of use cases and applications where traditional power sources are unsuitable. The diamond battery also has the potential to improve healthcare by powering various implants like hearing aids, pacemakers, and ophthalmic devices. Unlike regular batteries, which require frequent replacement, the diamond battery has the potential to keep working for centuries, decreasing patient discomfort and risks associated with surgery.

These batteries are also perfect for missions in space and isolated locations on Earth. They could potentially supply power to spacecraft, satellites, and even RF tags, significantly lowering costs and increasing operating life. Micropower technology can enable a wide range of essential applications, including space technology, medical implants, and security devices.

A Sustainable Energy Source Solution

The carbon-14 used in diamond batteries is derived from graphite blocks. These blocks are a byproduct of nuclear fission reactors. Recycling this radioactive material decreases nuclear waste while also providing a valuable energy source. The United Kingdom alone has about 95,000 tons of graphite blocks. advanced technology developed by a collaboration between the University of Bristol and the UKAEA. This technique not only gives radioactive waste a useful purpose, but it also lowers the expense and storage issues.

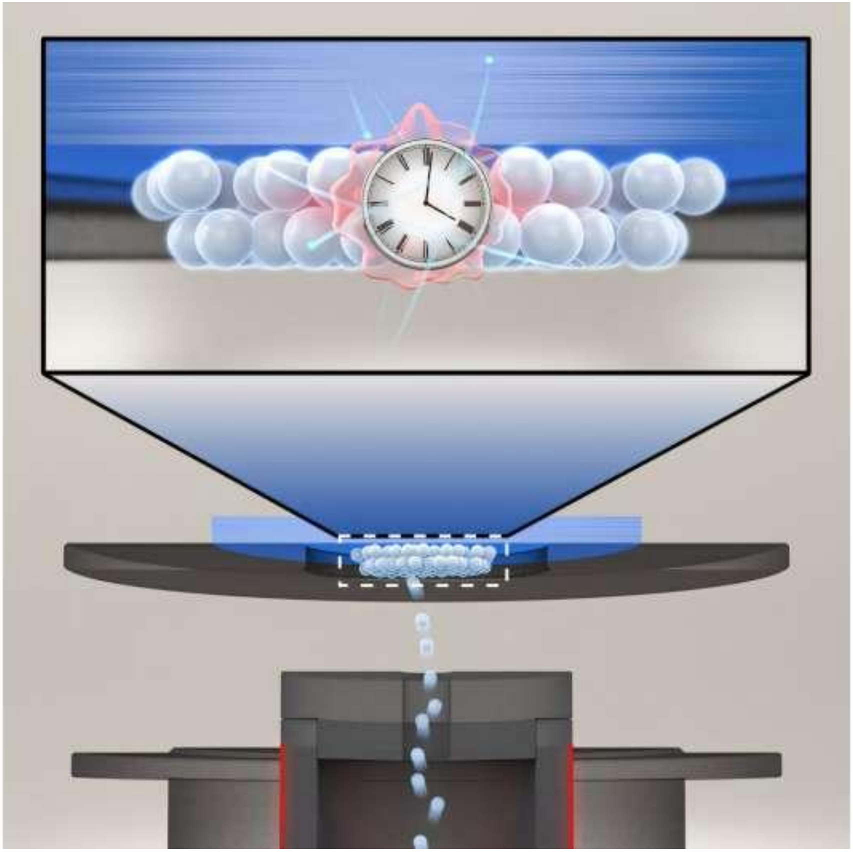
Revolutionary and Safe Technology

The diamond battery is not only a scientific wonder but also a reliable energy source. The diamond casing completely absorbs the short-range radiation, resulting in no hazardous emissions. Even if disposal is required, the battery can be sent back to the manufacturer and safely recycled. This new development, which combines scientific skills with innovative engineering, is expected to completely alter the future of energy. These diamond batteries, which will one-day power medical gadgets, spaceships, and distant sensors, present a glimpse into a cleaner and more sustainable future.

The post World's First 5,700-Year-Lifespan Nuclear Diamond Battery Revealed by UK Researchers appeared first on The Hearty Soul.

DECEMBER 18, 2024

Thin-film tech makes nuclear clocks a 1,000 times less radioactive and more affordable



A schematic of the deposition process, as thorium ions get vaporized then deposited in a thin film on the substrate's surface. Credit: Steven Burrows/Ye group and JILA

In the quest for ultra-precise timekeeping, scientists have turned to nuclear clocks. Unlike optical atomic clocks—which rely on electronic transitions—nuclear clocks utilize the energy transitions in the atom's nucleus, which are less affected by outside forces, meaning this type of clock could potentially keep time more accurately than any previously existing technology.

However, building such a clock has posed major challenges—thorium-229, one of the isotopes used in nuclear clocks, is rare, radioactive, and extremely costly to acquire in the substantial quantities required for this purpose.

Reported in a study published in *Nature,* a team of researchers, led by JILA and NIST Fellow and University of Colorado Boulder Physics professor Jun Ye, in collaboration with Professor Eric Hudson's team at UCLA's Department of Physics and Astronomy, have found a way to make nuclear clocks a thousand times less radioactive and more cost-effective, thanks to a method creating thin films of thorium tetrafluoride (ThF_4).

The successful use of thin films marks a potential turning point in the development of nuclear clocks. Using thin-film technology in nuclear clocks is commensurate with semiconductors and photonic integrated circuits, suggesting that future nuclear clocks could be more accessible and scalable.

"A key advantage of nuclear clocks is their portability, and to fully unleash such an attractive potential, we need to make the systems more compact, less expensive, and more radiation-friendly to users," said Ye.

The costs of nuclear clockmaking

JILA has been at the forefront of atomic and optical clock research for decades, with Ye's laboratory making pioneering contributions to advancing the concept, design, and implementation of optical lattice clocks, which set new standards in precision timekeeping.

Physicists have been trying to observe the energy transition of thorium-229 for nearly 50 years. In September 2024, researchers in Ye's laboratory reported the first high-resolution spectrum of the nuclear transition and determined the absolute frequency based on the JILA Sr optical lattice clock.

Their result was published as a cover article in *Nature*.

To build their nuclear clock setup, the team worked with radioactive thorium-229 crystals, collaborating with researchers at the University of Vienna.

"The growth of that crystal is an art in itself, and our collaborators in Vienna spent many years of effort to grow a nice single crystal for this measurement," explains Chuankun Zhang, a graduate student at JILA and first author of both *Nature* studies.

Previous approaches using thorium-doped crystals required more radioactive material. As thorium-229 is often sourced from uranium via nuclear decay, this leads to additional radiation safety and cost considerations.

"Thorium-229 by weight is more expensive than some of the custom proteins I've worked with in the past," adds JILA postdoctoral researcher Jake Higgins, also involved in this project, "so we had to make this work with as little material as possible." The researchers collaborated closely with CU Boulder's Environmental Health & Safety department to safely build and study their nuclear clock.

As the team worked to observe the nuclear transitions in thorium-doped crystals, they simultaneously pursued methods to make the clock safer and more cost-effective by developing thin film coatings to reduce the amount of radioactive thorium needed.

Vaporizing thorium

To produce the thin films, the researchers used a process called physical vapor deposition (PVD), which involved heating thorium fluoride in a chamber until it vaporized. The vaporized atoms then condensed on a substrate, forming a thin, even layer of thorium fluoride about 100 nanometers thick.

The researchers selected sapphire and magnesium fluoride as substrates because of their transparency to the ultraviolet light used to excite the nuclear transition.

"If we have a substrate very close by, the vaporized thorium fluoride molecules touch the substrate and stick to it, so you get a nice, even thin film," Zhang says.

This method used just micrograms of thorium-229, making the product a thousand times less radioactive while producing a dense layer of active thorium nuclei. Working with the JILA Keck Metrology laboratory and JILA instrument maker Kim Hagen, the researchers reliably reproduced films that could be tested for potential nuclear transitions using a laser.

Finding energy transitions in thin film

However, the team faced a new challenge. Unlike in a crystal, where every thorium atom was situated in an ordered environment, the thin films produced variations in thorium environments, shifting their energy transitions and making them less consistent.

JILA graduate student Jack Doyle, who was also involved in this study, elaborates, "Wolfgang Pauli was rumored to have said that 'God invented the bulk and the surface is of the devil,' but he might as well have said this because the number of factors that are hard to learn about for a particular surface is immense."

After preparing the films, JILA researchers sent them to Professor Eric Hudson at UCLA, who used a high-power laser with a much greater spectral width to test the nuclear transitions.

This broad-spectrum laser has all of its optical power concentrated in one spectral location instead of a frequency comb that has regularly spaced spectral lines over a larger spectral distance. This allowed the UCLA team to excite the thorium nuclei effectively, even though the observed linewidth is broader than previously seen in the previous study.

When the laser's energy precisely matched the energy required for the transition, the nuclei emitted photons as they relaxed back to their original state. By detecting these emitted photons, the researchers could confirm successful nuclear excitations, verifying the thin film's potential to serve as a frequency reference for nuclear clocks.

"We made the thin film, we characterized it, and it looked pretty good," explains JILA graduate student Tian Ooi, who was also involved in this research. "It was cool to see that the nuclear decay signal was actually there."

A new chapter of precision timekeeping

Based on their findings, the researchers are excited about the improvements in precision timekeeping to be gained by using thin films in nuclear clocks.

"The general advantage of using clocks in a solid state, as opposed to in a trapped-ion setting, is that the number of atoms is much, much larger," Higgins elaborates. "There are orders and orders of magnitude more atoms than one could feasibly have in an ion trap, which helps with your clock stability."

These thin films could additionally allow nuclear timekeeping to move beyond laboratory settings by making them compact and portable.

"Imagine something you can wear on your wrist," Ooi says. "You can imagine being able to miniaturize everything to that level in the far, far future."

While this level of portability is still a distant goal, it could revolutionize sectors that rely on precise timekeeping, from telecommunications to navigation.

"If we are lucky, it might even tell us about new physics," Doyle adds.

More information: Eric Hudson, 229ThF4 thin films for solid-state nuclear clocks, *Nature* (2024). DOI: 10.1038/s41586-024-08256-5. www.nature.com/articles/s41586-024-08256-5
Journal information: Nature
Provided by JILA

AI robotics will take on human labor so humans can ‘engage their brains better,’ former Amazon exec says

Robots will replace human labor, to some extent and over time, but people shouldn’t be too worried, according to a long-time Amazon executive with a new AI supply chain start-up.

“Robotics will drive a ton in labor savings over time,” Dave Clark, the former CEO of Amazon’s consumer business and now founder of the AI supply-chain start-up auger, said Monday during Fortune’s Brainstorm AI conference in San Francisco. “Unfortunately, we've made productivity sort of a dirty word. But we keep finding better ways to engage people’s brains."

“There's too much hand wringing about it,” Clark added, alluding to expert warnings and concerns that future advances in AI technology may reduce or replace human labor to the benefit of corporations looking to save money on wages.

With two decades experience as a supply-chain executive, Clark admitted that companies are always looking to “extract maximum cost out of the system,” but the cost of labor is actually less impactful than things like transportation and a lack of forecasting.

Real-world humanoid locomotion with reinforcement learning

Editor's summary

The ability of robots to navigate adaptively and robustly in varying terrain increases their chances of success when deployed in the real world. However, stable locomotion of full-size bipedal humanoid robots creates a challenge from a controls perspective. Radosavovic *et al*. developed a reinforcement learning approach for controlling locomotion of a humanoid robot, Digit. They trained their model in simulation and subsequently deployed it into the real-world zero-shot and showed the potential for robust locomotion on various indoor and outdoor environments. The robot could exhibit natural and adaptive walking behaviors, including an emergent arm-swing motion, and adapt to external perturbations. —Amos Matsiko

Abstract

Humanoid robots that can autonomously operate in diverse environments have the potential to help address labor shortages in factories, assist elderly at home, and colonize new planets. Although classical controllers for humanoid robots have shown impressive results in a number of settings, they are challenging to generalize and adapt to new environments. Here, we present a fully learning-based approach for real-world humanoid locomotion. Our controller is a causal transformer that takes the history of proprioceptive observations and actions as input and predicts the next action. We hypothesized that the observation-action history contains useful information about the world that a powerful transformer model can use to adapt its behavior in context, without updating its weights. We trained our model with large-scale model-free reinforcement learning on an ensemble of randomized environments in simulation and deployed it to the real-world zero-shot. Our controller could walk over various outdoor terrains, was robust to external disturbances, and could adapt in context.

OpenAI backed 1X’s humanoid robots showcase an advanced neural network

1X’s androids use Embodied Learning, integrating AI software directly into their physical forms for advanced capabilities.

Published: Feb 12, 2024 11:49 AM EST

1X aims to supply abundant supply physical labor through secure, intelligent androids.

To advance the labor landscape, robotics firm 1X has embarked on a mission to offer ample physical labor by utilizing safe and intelligent androids.

The OpenAI-backed firm 1X claims it prioritizes human-environment alignment, designing hardware resembling the human form for enhanced versatility. The company employs a comprehensive autonomy approach to maximize adaptable hardware potential, teaching motor behaviors directly from visual input via neural networks.

Having initially deployed this system on its first humanoid robot, EVE, for patrolling tasks back in 2023, 1X is now rolling out its latest advancements in the capabilities of its androids. According to the company, these enhancements have been acquired solely through end-to-end learning from data, marking a significant milestone in the evolution of robotics technology.

Advanced proposition

1X's androids, human-like robots, are crafted to resemble and imitate human actions, seamlessly navigating our environment. They adeptly handle everyday objects, maneuver through standard doorways, and seamlessly integrate into various settings to assist and enhance human activities.
1X's androids utilize Embodied Learning, an advanced AI approach directly integrating the company's AI software into their physical bodies. This integration enables the androids to autonomously interact with their environment, learning from real-world experiences and sensory inputs. Through a methodology termed 'shared autonomy,' human operators collaborate with AI to enhance the androids' capabilities. Operators employ VR teleoperation in 1X's Studio to train androids in various tasks, effectively merging human intelligence with AI efficiency.

The company trains its foundational models for embodied intelligence while integrating them with OpenAI's latest high-level planning and instruction comprehension models. The overarching objective is to equip androids with the ability to comprehend and execute tasks via voice commands, catering to diverse applications ranging from household chores to industrial settings.

Neural network

In the video demonstration shared by the firm, 1X claims that the humanoid's every behavior is governed by a single vision-based neural network operating at 10Hz, controlling driving, arm movements, gripper function, torso adjustments, and head positioning. No teleoperation, computer graphics, video editing, or scripted trajectories are involved; all actions are autonomously executed by neural networks, operating at real-time speed, claims 1X.
To develop the machine learning models responsible for these behaviors, 1X curated a diverse and high-quality dataset comprising demonstrations from 30 EVE robots. Initially, a "base model" is trained on this dataset, imparting a broad understanding of various physical behaviors, ranging from household chores to social interactions with humans and other robots.

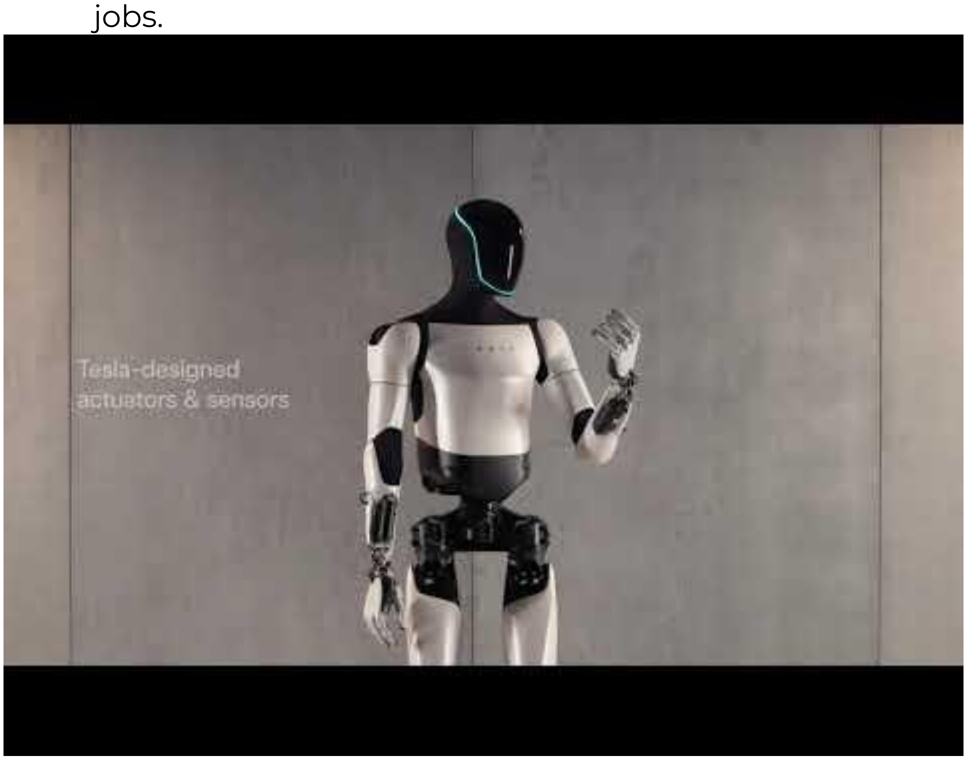
Subsequently, this base model undergoes fine-tuning to specialize in specific families of capabilities, such as general door manipulation or warehouse tasks. Further fine-tuning aligns these capabilities with solving precise tasks, such as opening a specific door, according to the company.

This training strategy enables rapid onboarding of new skills with minimal data collection and training time, utilizing desktop GPUs. The firm claims that "all capabilities showcased in the video are trained by android operators, embodying a new generation of "Software 2.0 Engineers" who express robot capabilities through data rather than traditional coding methods. This approach liberates the company from constraints posed by the number of AI engineers, fostering flexibility in the range of tasks their androids can undertake for customers," said 1X in a statement.

The Dawn of Humanoid Robotics: 2024 Marks a Surge in AI-Enhanced Capabilities

A Look into the Future: Five Humanoid Robots Poised to Transform Our World

- **Advanced Humanoid Robotics**: In 2024, the field of robotics will see significant advancements, particularly in humanoid robots equipped with AI brains, thanks to developments in large language models (LLMs).
- **Notable Innovations**: Tesla's Optimus Gen-2 and Boston Dynamics' Atlas represent some of the leading innovations in humanoid robotics, showcasing enhanced speed, agility, and sensory capabilities.
- **Broadening Applications**: These robots are being designed not only for industrial applications but also for roles in everyday human environments, potentially addressing labor shortages and improving safety in hazardous jobs.

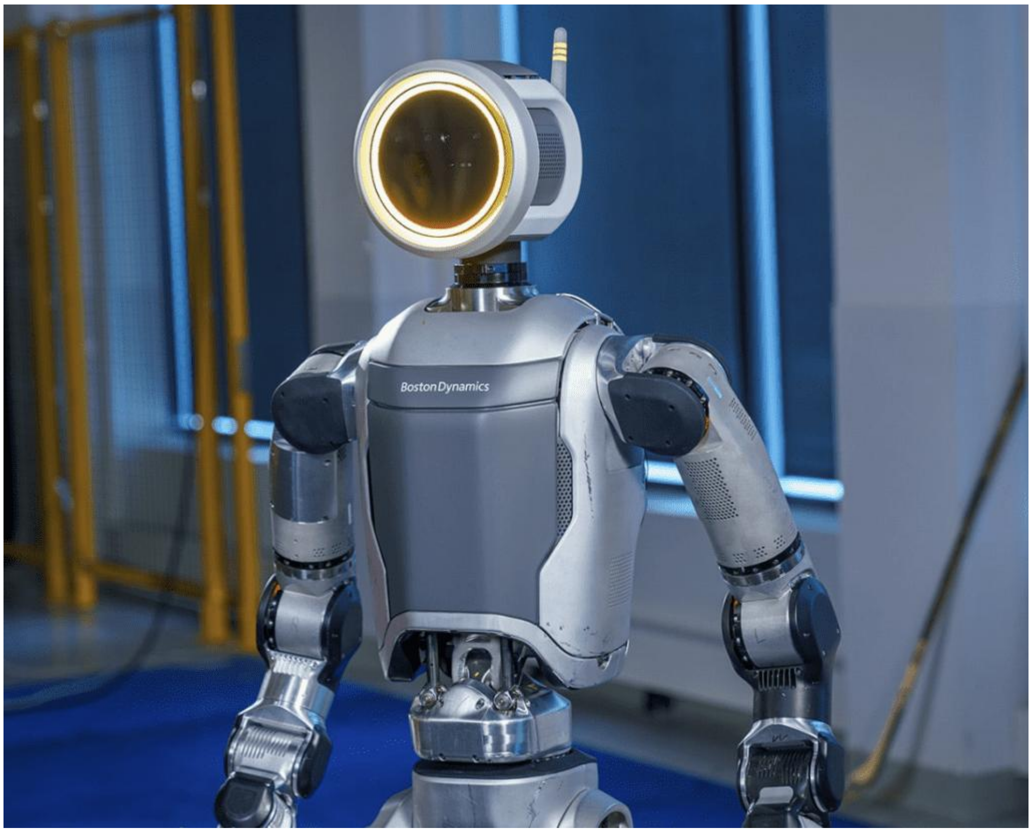


Tesla's Optimus

The age of robots is not just approaching; it is already upon us, with 2024 slated to be a landmark year for advancements in humanoid robotics. As large language models (LLMs) integrate deeper into robotic systems, these AI-driven machines are becoming more sophisticated, capable, and poised to take on roles that have traditionally been the domain of humans.

Technological Breakthroughs in Humanoid Robotics

Among the standout innovations are Tesla's Optimus Gen-2 and Boston Dynamics' Atlas. The Optimus Gen-2, Tesla's latest iteration, boasts significant improvements over its predecessors, including a 30% increase in walk speed, enhanced balance, and tactile sensing on all fingers, allowing for delicate object manipulation such as holding an egg without breaking it. These enhancements underline the rapid progression from the prototype stages to more refined and capable versions.



Boston Dynamics continues to push the boundaries with Atlas, its fully electric robot that combines advanced control systems and state-of-the-art hardware to exhibit remarkable athletic abilities and agility. Atlas is not only a testament to the potential of robots in performing complex physical tasks but also demonstrates the feasibility of humanoid robots working alongside humans in various settings.

Emerging Players in the Robotics Field

Other notable robots making waves include Figure 01 by Figure robot, H1 by Unitree Robotics, and the Fourier GR-1. Each of these robots brings unique capabilities to the table, from Figure 01's general-purpose utility in the workforce to H1's exceptional power performance and mobility in complex terrains, and GR-1's highly bionic motion control capabilities.

Implications and Future Prospects

The implications of these advancements are profound. Humanoid robots are transitioning from novelty to necessity, finding their place not just in factories and labs but in everyday settings, addressing critical issues such as labor shortages and workplace safety. The integration of AI not only enhances the functionality of these robots but also ensures they can perform tasks with a level of precision and efficiency that rivals human capability.

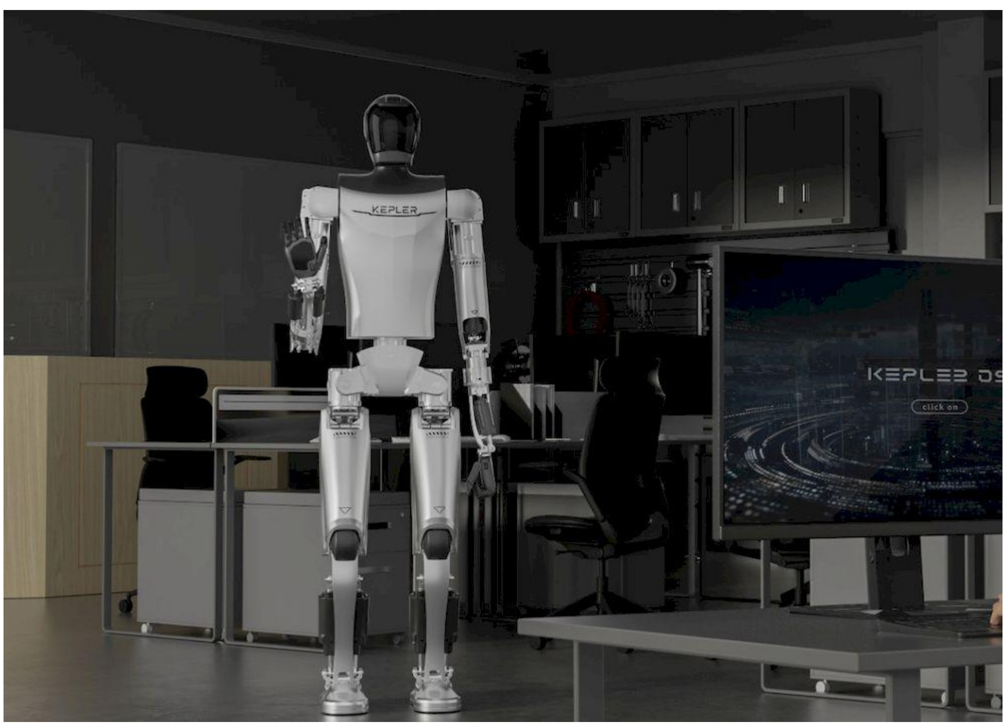
As we move into 2024 and beyond, the landscape of humanoid robotics is set to transform dramatically. With each technological leap, robots like Tesla's Optimus Gen-2 and Boston Dynamics' Atlas are not only redefining what machines can do but are also reshaping the interactions between humans and machines, heralding a new era of coexistence and cooperation.

Discover the Top 10 Cutting-Edge Humanoid AI Robots of 2024/2025

Explore the latest advancements in humanoid AI robots for 2024 and 2025. Discover how these innovative machines are set to transform daily tasks and redefine our interactions with technology.

The world of robotics is evolving at an astonishing pace, with humanoid AI robots leading the charge into the future. From assisting in daily tasks to performing complex operations, these robots are designed to enhance productivity and redefine our interactions with technology. Here's a look at ten of the most advanced humanoid robots set to make waves in 2024 and 2025.

Kepler Humanoid Robot



The **Kepler Humanoid Robot** is a groundbreaking innovation that aims to revolutionize everyday tasks. Designed to navigate its surroundings with ease, this robot is equipped with high-definition cameras and sensors that allow it to identify objects and execute tasks efficiently. Whether it's assisting in emergency rescues or monitoring security, the Kepler robot is versatile enough to handle various roles, including operating in harsh outdoor conditions.

With its potential to upgrade to more advanced models, the Kepler robot is not just a tool but a glimpse into the future of robotics. Its ability to reduce human labor in production lines and perform complex tasks makes it a valuable asset in any operational environment.

LimX Dynamics CL-1

Next up is the **LimX Dynamics CL-1**, a humanoid robot that stands out with its sleek design and impressive capabilities. One of its most remarkable features is its ability to climb stairs, making it suitable for diverse environments. The CL-1 is equipped with real-time perception and gait planning control, allowing it to navigate busy streets and conduct meetings seamlessly.

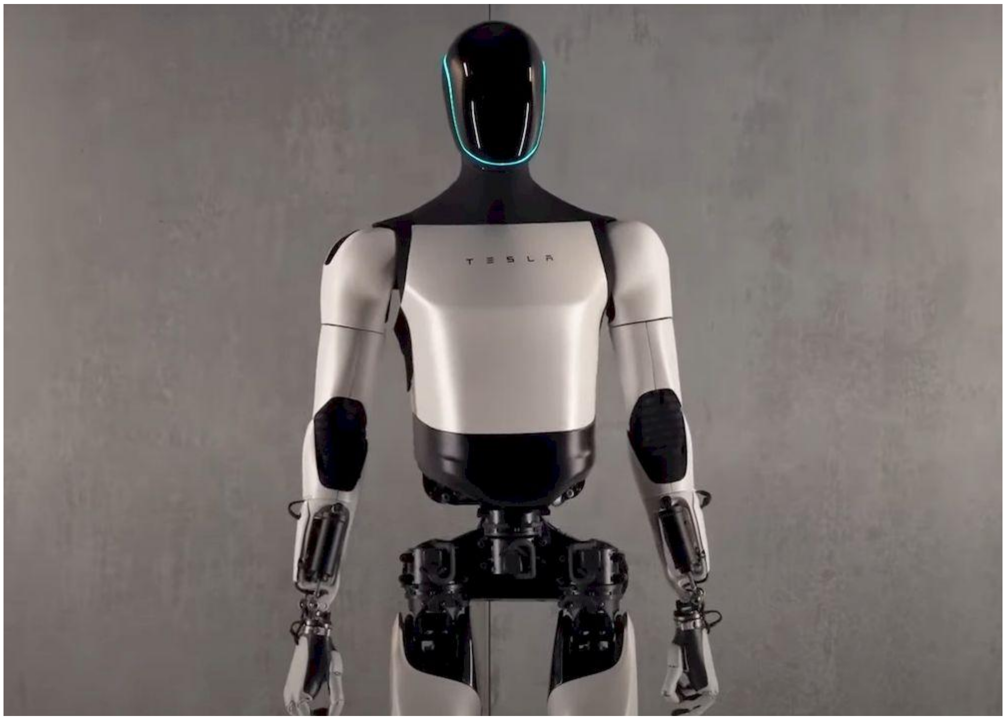
This robot is not just about looks; it can handle delicate items with care and is constantly learning through machine learning algorithms. As it evolves, the LimX Dynamics CL-1 is set to take on more manual tasks, ensuring that human labor becomes a thing of the past.

Fourier GR-1

The **Fourier GR-1** is a mass-produced humanoid robot that boasts a bionic torso and human-like motions. With a torque of 230 Nm, it can walk briskly and navigate obstacles with ease. This robot is designed for high-performance tasks, whether it's stacking boxes in a warehouse or even competing in a soccer league.

What sets the GR-1 apart is its ability to perform tasks that require precision and agility. It's a perfect example of how robotics can replace human labor in various sectors, making it an essential tool for the future.

Optimus Gen 2



Tesla's **Optimus Gen 2** is not just another electric vehicle; it's a glimpse into the future of robotics. This prototype features an actuated neck and multiple sensors that allow it to handle delicate objects with precision. From sewing to preparing meals, the Optimus Gen 2 is designed to take on a variety of tasks that require a human touch.

In the near future, this robot will be capable of delivering packages, preparing food, and even walking dogs. The versatility of the Optimus Gen 2 makes it a game-changer in the world of humanoid robots, promising a future where robots seamlessly integrate into our daily lives.

Astribot S1

The **Astribot S1** is your personal robot chef, designed to prepare gourmet meals without the need for human intervention. This robot can cook, clean, and even assist with household chores, making it an invaluable addition to any home. Its ability to operate various kitchen appliances and perform delicate tasks sets it apart from traditional cooking methods.

Imagine coming home to a freshly prepared meal, thanks to your Astribot S1. This robot not only saves time but also ensures that your culinary needs are met with precision and care, making it a must-have for busy households.

Thermonator

Say hello to the **Thermonator**, a robotic dog that comes with a fiery twist. Equipped with an arc flamethrower, this quadruped robot is designed to control wildfires while also being capable of performing various tasks. From melting snow to providing warmth, the Thermonator is a versatile tool for outdoor operations.

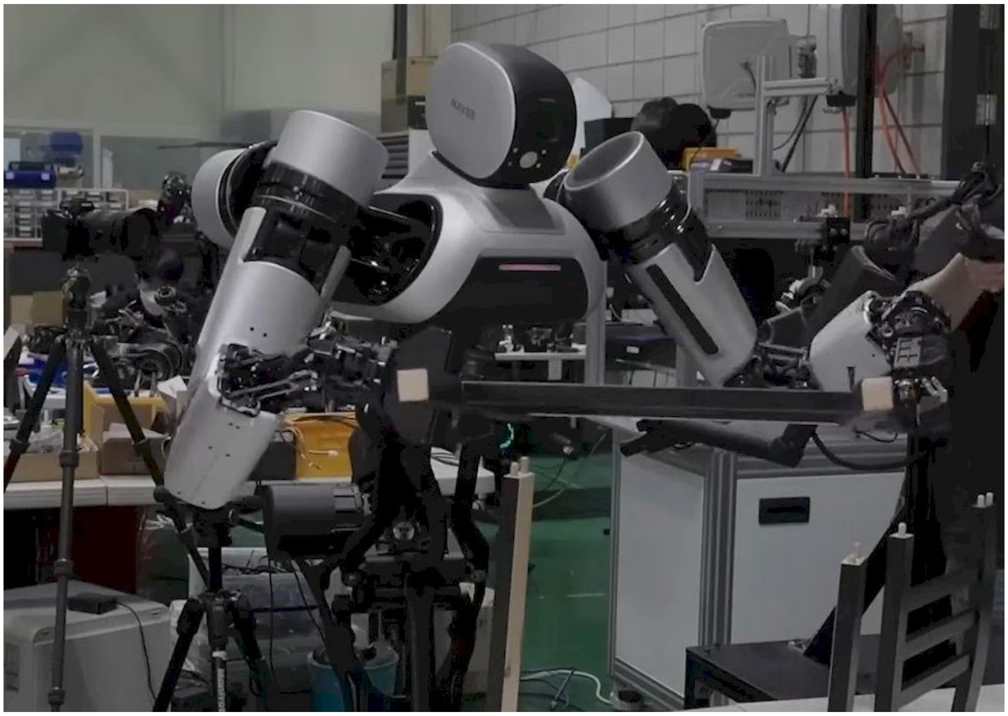
Controlled via a smartphone, this robot can navigate complex terrains and perform tasks with precision. Its ability to operate under various conditions makes it an essential asset for emergency services and outdoor activities.

Figure

The **Figure** is a general-purpose humanoid robot that can perform a wide range of tasks, from meal preparation to package delivery. With its shiny silver exterior, it’s not just functional but also visually striking. This robot is designed to assist in warehouses and homes alike, ensuring that daily tasks are completed efficiently.

Imagine having a robot that can lift heavy boxes and sort laundry while also preparing your meals. The Figure is the perfect blend of utility and design, making it a valuable addition to any household or business.

AMBIDEX



Meet **AMBIDEX**, the ambidextrous robot that can perform tasks with both hands equally well. This innovative robot is learning human movements and can assist in various activities, from washing dishes to playing sports. Its ability to adapt and learn makes it a promising addition to the world of robotics.

AMBIDEX is not just a helper; it's a companion that can enhance your daily life. Whether you need assistance in the kitchen or a sports coach, this robot is designed to meet your needs and improve your skills.

RB-Y1 by Rainbow Robotics

The **RB-Y1** is a fun and functional robot that can stack cups, clean up messes, and even provide piggyback rides. Developed by Rainbow Robotics, this robot is designed for entertainment and utility, making it a great addition to any home or workplace.

With its ability to perform various tasks and its playful nature, the RB-Y1 is not just a robot; it’s a companion that can bring joy and efficiency to your daily routine. Its unique features make it a standout in the world of robotics.

CyberOne

Finally, we have the **CyberOne**, a humanoid robot that understands human emotions. Weighing only 51 kg and standing 177 cm tall, this robot can perform tasks while also being attuned to your feelings. Its advanced sensors allow it to navigate its environment and interact with humans in a meaningful way.

The CyberOne is designed to be more than just a tool; it's a companion that can provide emotional support and assistance. With its ability to understand gestures and emotions, this robot is paving the way for a future where technology and humanity coexist harmoniously.

As we look ahead to the end of 2024 and 2025, these humanoid robots are set to transform our lives in ways we can only begin to imagine. With their unique capabilities and advanced technology, they promise to enhance productivity, improve efficiency, and redefine our interactions with the world around us.

10 Amazing Humanoid Robots in 2024

In 2024, the field of humanoid robotics has reached new heights, with groundbreaking advancements in agility, dexterity, social interaction, and artificial intelligence. These ten remarkable humanoid robots are poised to transform various industries and everyday life. From disaster relief and construction to household automation and customer service, these robots showcase the incredible potential of robotics technology.

Atlas (Boston Dynamics)

Boston Dynamics' Atlas robot is a marvel of agility and precision. The latest iteration of Atlas is fully electric, replacing the previous hydraulic model, which significantly enhances its strength, agility, and range of motion. Atlas's advanced control systems and dynamic balancing capabilities allow it to navigate complex terrains and perform tasks with unparalleled stability.

This makes it an ideal candidate for disaster relief operations, construction sites, and search and rescue missions. Atlas's ability to maintain balance and adapt to different tasks on the fly sets it apart, allowing it to tackle challenges that were previously impossible for robots. With ongoing developments and partnerships, such as with Hyundai for testing in automotive manufacturing, Atlas continues to push the boundaries of what humanoid robots can achieve.

Spot (Boston Dynamics)

Spot, another innovation from Boston Dynamics, is renowned for its versatility and adaptability. Unlike Atlas, Spot is a four-legged robot designed to excel in various applications, including industrial inspection, data collection, and emergency response. Spot's 360° perception and autonomous navigation capabilities enable it to traverse difficult terrain and access areas that are hazardous or inaccessible to humans.

This makes Spot an invaluable asset in industries that require precise and reliable data collection in challenging environments. The robot's robust design and ability to operate in diverse conditions demonstrate its potential to significantly enhance safety and efficiency in multiple sectors.

Optimus (Tesla)

Tesla’s Optimus represents the company’s ambitious entry into the realm of general-purpose humanoid robots. Designed to simplify everyday tasks and provide companionship, Optimus aims to revolutionize household automation. While still in the early stages of development, Optimus’s potential is immense.

Tesla envisions a future where Optimus can perform a wide range of tasks, from assisting with daily chores to providing social interaction and support. The development of Optimus leverages Tesla’s expertise in AI and robotics, promising to integrate advanced technologies that enhance the robot’s functionality and user experience. As development progresses, Optimus could transform how we live and interact with technology, making sophisticated robotic assistance a common feature in households.

Digit (Agility Robotics)

Digit, developed by Agility Robotics, is a collaborative robot that features dexterous arms and advanced perception capabilities. Digit’s ability to manipulate objects with precision makes it well-suited for applications in warehouses, factories, and construction sites. Its design allows it to work seamlessly alongside humans, enhancing productivity and safety in industrial settings.

Digit’s advanced perception systems enable it to navigate complex environments and perform a variety of tasks, from material handling to intricate assembly operations. The robot’s collaborative nature and adaptability highlight its potential to revolutionize industrial workflows, making processes more efficient and reducing the physical strain on human workers.

Pepper (SoftBank Robotics)

Pepper, the humanoid robot from SoftBank Robotics, specializes in social interaction and emotional recognition. Widely deployed in customer service, healthcare, and education, Pepper engages with humans meaningfully through advanced facial recognition and voice analysis technologies. Its ability to provide assistance and companionship makes it a valuable asset in various sectors. In customer service, Pepper can greet and assist customers, enhancing their experience and providing valuable information. In healthcare, Pepper can offer companionship and monitor patients’ well-being, contributing to improved care and patient outcomes. The robot’s interactive capabilities and empathetic design make it an important tool for enhancing human-robot interactions in everyday life.

Figure 01 (Figure)

Figure 01 is a humanoid robot that focuses on fine motor skills and problem-solving. Its highly articulated hands and precise movements, powered by an advanced AI system, enable it to perform tasks requiring high levels of dexterity and adaptability. Figure 01's capabilities make it suitable for applications in research, manufacturing, and beyond. The robot's advanced AI system allows it to learn and adapt to new tasks, improving its performance over time. This continuous learning ability ensures that Figure 01 remains relevant and effective in dynamic environments, where tasks and requirements can change rapidly. Its precise and adaptable nature positions Figure 01 as a valuable asset in fields that demand meticulous and flexible robotic assistance.

Apollo (Atronics)

Atronics' Apollo is a versatile humanoid robot designed to cater to the needs of various industries. With its energy-efficient design and modular architecture, Apollo can be easily customized for specific applications. Its capabilities include walking, running, and tool operation, making it a valuable asset in a wide range of settings. Apollo's modular design allows it to be tailored to different tasks, enhancing its utility and efficiency in diverse environments. The robot's ability to perform a variety of movements and operate tools highlights its potential to revolutionize workflows in industries such as manufacturing, logistics, and construction. Apollo's versatility and adaptability make it a promising solution for addressing complex industrial challenges.

Sanctuary AI Robot

The Sanctuary AI Robot is an advanced humanoid robot with the potential for Artificial General Intelligence (AGI). By learning from human demonstrations and excelling in problem-solving, this robot pushes the boundaries of what is possible in robotics. While many details about the Sanctuary AI Robot remain undisclosed, its potential to transform industries and shape the future is immense. The robot's ability to learn and adapt to new tasks through observation and interaction demonstrates its advanced cognitive capabilities. As the development of AGI progresses, the Sanctuary AI Robot could play a pivotal role in various sectors, providing intelligent and adaptable solutions to complex problems.

Unitree H1 (Unitree Robotics)

Unitree H1, developed by Unitree Robotics, is an affordable and capable humanoid robot designed to bring robotic assistance to a broader audience. With its advanced accessibility options and user-friendly interface, Unitree H1 is suitable for both everyday tasks and professional settings. The robot's affordability and ease of use make it an attractive option for households and businesses looking to integrate robotic assistance into their daily operations. Unitree H1's advanced features and intuitive design ensure that it can effectively perform a wide range of tasks, from basic household chores to more complex professional duties, enhancing efficiency and convenience for users.

Robot ERA

Watch this video on YouTube.

Robot ERA's robot employs an embodied AI approach that enables continuous learning and adaptation. Its versatility and ability to improve performance through experience make it a valuable asset in dynamic environments. Robot ERA focuses on data collection and task adaptability, making it well-suited for applications in research, exploration, and beyond. The robot's ability to learn from its interactions and refine its performance over time highlights its potential to contribute to a wide range of fields. By leveraging advanced AI and machine learning techniques, Robot ERA can adapt to new challenges and provide reliable and efficient assistance in various contexts.

These ten humanoid robots represent the pinnacle of robotics technology in 2024. Each robot brings unique capabilities and potential to transform various aspects of our lives, from disaster relief and industrial operations to household automation and social interaction. As these robots continue to evolve and push the boundaries of what is possible, they pave the way for a future where humans and robots work together seamlessly to address challenges and improve the world around us.

The Rise of Humanoid Robots in 2024: A Multifaceted Perspective

Exploring the driving forces behind the burgeoning field of humanoid robotics and the associated challenges and implications for society.

Summary: As humanoid robotics garners momentum in 2024, the convergence of technological advances, societal needs, and economic incentives propels this AI domain, while raising significant ethical and practical concerns.

(AIM)—In 2024, humanoid robots represent a significant focal point in the field of artificial intelligence, underpinned by various driving factors that range from technical innovations to socio-economic demands. The evolution of humanoid robots is no longer relegated to the realms of science fiction; it is a tangible reality shaping multiple aspects of human life.

Technological Advances: Recent breakthroughs in AI subfields such as machine learning, computer vision, and natural language processing have significantly enhanced the capabilities of humanoid robots. These technological strides enable robots to perform complex tasks with greater autonomy and precision, closely mimicking human actions and interactions.

Societal Needs: The growing prevalence of aging populations and labor shortages across the globe has catalyzed the adoption of humanoid robots. These robots are increasingly seen as viable solutions for caregiving, service roles, and even in search and rescue operations, where human intervention might be risky or insufficient.

Economic Drivers: From an economic standpoint, the potential for humanoid robots to revolutionize industrial automation, home services, and entertainment sectors has attracted substantial investment from both startups and established companies, aiming to capitalize on their commercial applications.

Research and Academic Interest: Academic institutions and researchers are deeply invested in advancing humanoid robot technology. This surge in scholarly interest fosters further innovation, particularly in improving robot mobility, dexterity, and decision-making processes.

Policy and Government Support: Government initiatives in several countries provide critical support for AI and robotics research through funding and policy frameworks. This support not only accelerates technological advancements but also helps in addressing regulatory and ethical standards necessary for integrating robots into society.

Ethical and Legal Considerations: As humanoid robots become more integrated into daily life, ethical and legal issues come to the forefront. Concerns about job displacement, privacy, and security require thoughtful consideration to balance technological progress with societal welfare.

Public Acceptance and International Competition: The global race to dominate this frontier technology compels nations to invest heavily in humanoid robotics. Public acceptance is gradually increasing as people become more familiar with robots performing everyday tasks and providing companionship or assistance.

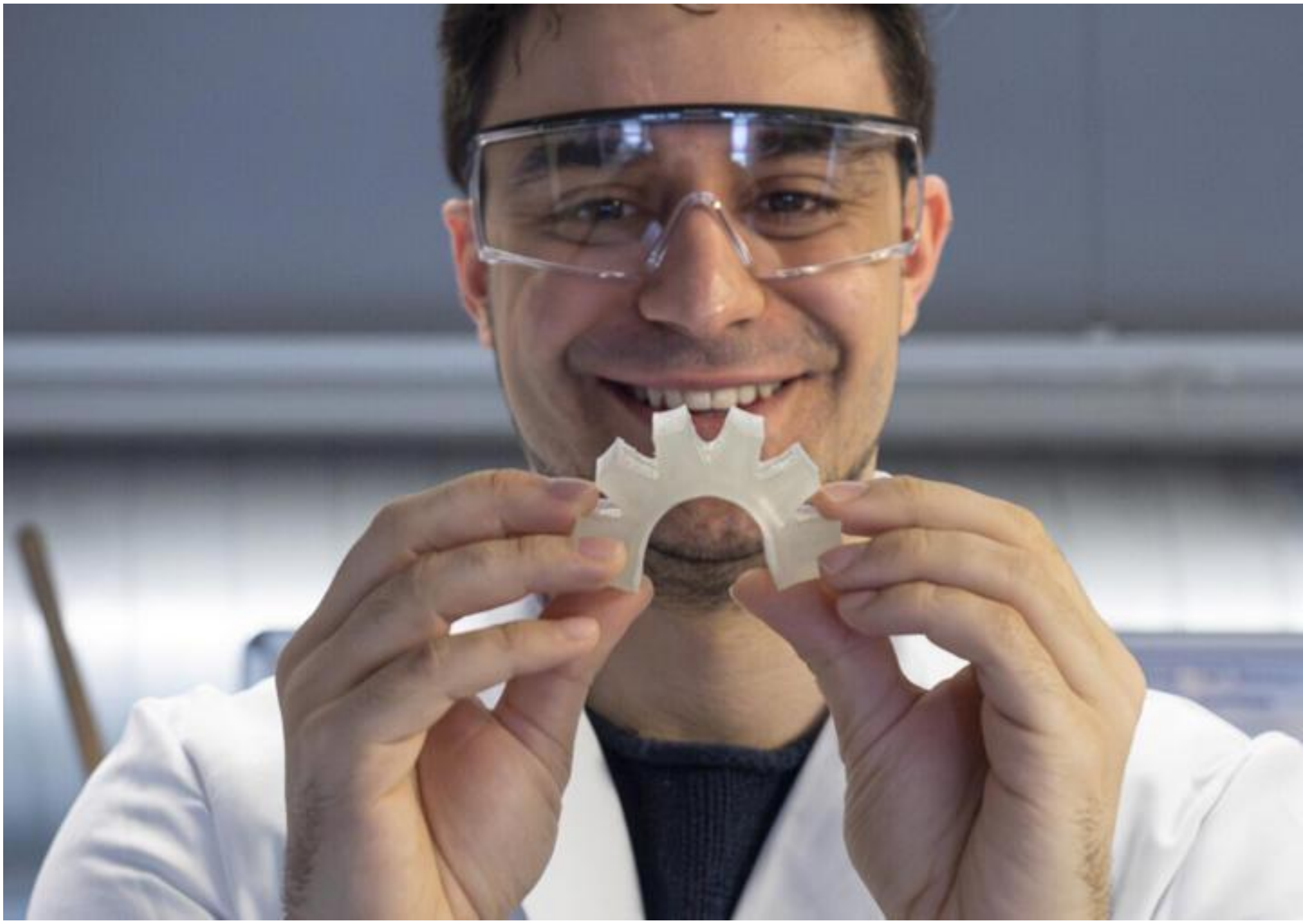
Challenges and Concerns: Despite the excitement surrounding humanoid robots, several challenges persist. Technical limitations, high manufacturing costs, and safety concerns need to be systematically addressed. Moreover, ethical dilemmas surrounding robot autonomy and potential misuse underscore the need for robust ethical frameworks and regulations.

Humanoid robots in 2024 are at a pivotal juncture, promising to reshape industries and societal norms. While the opportunities are vast, the path forward requires a balanced approach that considers the technical, economic, and ethical dimensions of robot integration into human environments.

Sensitive ceramics for soft robotics: Developing soft and intelligent sensor materials based on ceramic particles

Empa researcher Frank Clemens and his team develop soft and intelligent sensors materials based on ceramic particles. Credit: Empa

Most people think of coffee cups, bathroom tiles or flower pots when they hear the word "ceramic." Not so Frank Clemens. For the research group leader in Empa's Laboratory for High-Performance Ceramics, ceramics can conduct electricity, be intelligent, and even feel.



Empa researcher Christopher Bascucci demonstrates a soft material which can be enhanced with ceramic sensors. Credit: Empa

Together with his team, Clemens is developing soft sensor materials based on ceramics. Such sensors can "feel" temperature, strain, pressure or humidity, for instance, which makes them interesting for use in medicine, but also in the field of soft robotics. This work was published in the journal *Advanced Intelligent Systems*.

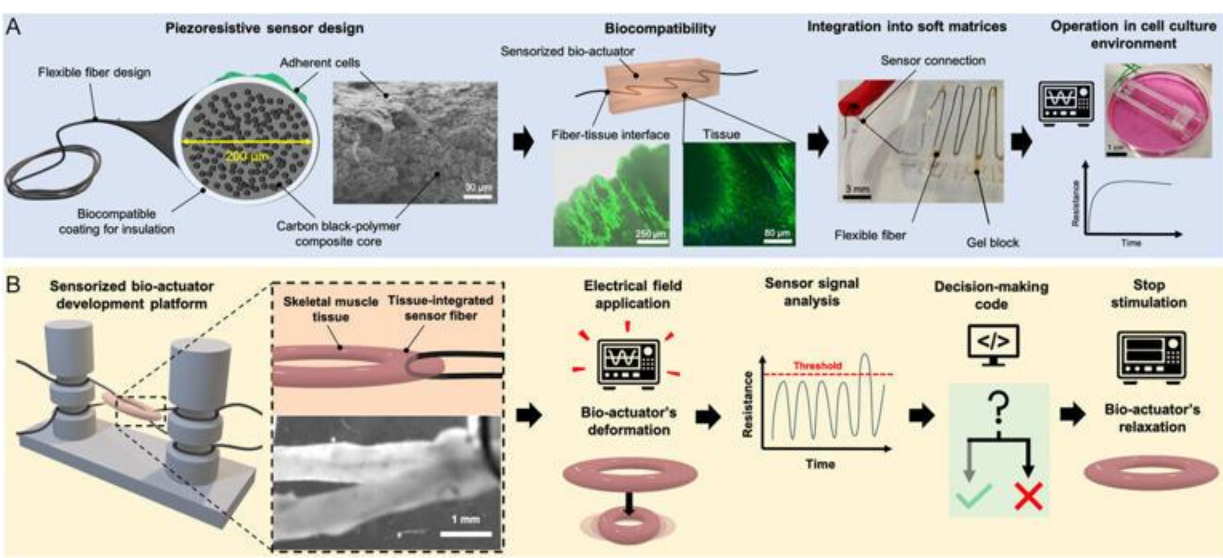
Soft ceramics—how is that supposed to work? Materials scientists like Clemens define ceramics as an inorganic, non-metallic material that is produced from a collection of loose particles in a high-temperature process known as sintering.

The composition of ceramics can vary—and their properties change as a result. But earthenware and porcelain are nowhere to be seen in Clemens' lab. The researchers work with materials such as potassium sodium niobate and zinc oxide, but also with carbon particles.

None of these materials are soft. In order to fashion them into flexible sensors, the researchers embed ceramic particles in stretchable plastics.

"We work with so-called highly filled systems," says Clemens. "We take a matrix made of a thermoplastic and fill it with as many ceramic particles as possible without compromising the elasticity of the matrix."

If this highly filled matrix is then stretched, compressed or exposed to temperature fluctuations, the distance between the ceramic particles changes, and with it the electrical conductivity of the sensor. It's not necessary to fill the entire matrix with ceramic, emphasizes Clemens: Using 3D printing, the researchers can also embed the ceramic sensors as a kind of "nerves" in flexible components.



Realization of a proprioceptive system in a skeletal muscle tissue-based bioactuator. A) The mechanosensor uses a piezoresistive composite designed as a silicone-insulated fiber. The fiber was characterized by its sensing performance, integrability in soft matrices, biocompatibility in engineered skeletal muscle tissue, and operativity in a cell culture environment. B) When assembled with bioactuators, the sensor revealed micromotions triggered by electrical stimulation without disturbance from applied electrical fields, and the sensor signal could be used to modulate the stimulation pulses provided by muscle electrical stimulation setup. Credit: Advanced Intelligent Systems (2024). DOI: 10.1002/aisy.202400413

Selective and intelligent

The production of soft ceramic sensors is not trivial. Usually, soft sensors are sensitive to different environmental influences at the same time, such as temperature, strain and humidity. "If you want to use them in practice, you need to know what you are measuring," says Clemens. His research group has succeeded in producing soft sensors that react very selectively only to pressure or only to temperature.

The researchers integrated these sensors into a prosthetic hand. The prosthesis "senses" the flexion of its fingers and notices when it touches a hot surface. Such "sensitivity" would be an advantage both for robotic gripping tools and for human prostheses.

The Empa team even went one step further with the development of a soft "robot skin." Similar to human skin, the multi-layered plastic skin reacts to touch and temperature differences.

In order to evaluate the complex data, the Empa researchers developed an AI model together with researchers from the University of Cambridge and trained it using data from around 4,500 measurements. This is also reminiscent of human perception, as the nerve impulses from our skin are evaluated and extrapolated in the brain.

In their most recent project, the researchers were able to combine the ceramic sensors with artificial muscles. Together with researchers from ETH Zurich and the University of Tokyo, they have developed a bio-hybrid robot that recognizes its contraction state with the help of a soft, biocompatible, tissue-integrated piezoresistive sensor.

Safe collaboration between humans and machines

The aim, says Frank Clemens, is for humans and machines to work together safely and harmoniously. "Today's robotic systems are big, clunky and very strong. They can be dangerous for humans," explains the researcher. If in future we are to increasingly share our workplaces with robots, they should react quickly and sensitively to touch.

"If you accidentally touch another person, you automatically pull away," says Clemens. "We want to give robots the same reflex."

The researchers are now looking for industrial partners in the field of robotic gripping systems. But soft sensors are also in demand in medicine—the team recently completed an Innosuisse project with the company IDUN Technologies, in which they produced flexible electrodes for brain wave measurements.

The work is far from over: The researchers want to make their soft ceramic sensors even more sensitive and intelligent. This involves combining new ceramic materials and soft polymers and optimizing their sensor properties. The secret to success lies in the interaction of these two components.

More information: Miriam Filippi et al, Sensor-Embedded Muscle for Closed-Loop Controllable Actuation in Proprioceptive Biohybrid Robots, *Advanced Intelligent Systems* (2024). DOI: 10.1002/aisy.202400413

Provided by Swiss Federal Laboratories for Materials Science and Technology

IEEE/CAA Journal of Automatica Sinica

A journal of IEEE and CAA , publishes high-quality papers in English on original theoretical/experimental research and development in all areas of automation

Volume 11 Issue 2

Feb. 2024

IEEE/CAA Journal of Automatica Sinica

- JCR Impact Factor: **15.3**, Top 1 (SCI Q1)

  CiteScore: **23.5**, Top 2% (Q1)

  Google Scholar h5-index: 77, TOP 5

Article Contents

Article Navigation > IEEE/CAA Journal of Automatica Sinica > 2024 > 11(2): 301-328

Citation: Y. Tong, H. Liu, and Z. Zhang, "Advancements in humanoid robots: A comprehensive review and future prospects," *IEEE/CAA J. Autom. Sinica*, vol. 11, no. 2, pp. 301–328, Feb. 2024. doi: 10.1109/JAS.2023.124140

Advancements in Humanoid Robots: A Comprehensive Review and Future Prospects

doi: 10.1109/JAS.2023.124140

- Yuchuang Tong ,
- Haotian Liu ,

- Zhengtao Zhang

Funds: This work was supported by the National Natural Science Foundation of China (62303457,U21A20482), Project funded by China Postdoctoral Science Foundation (2023M733737), the National Key R&D Program of China (2022YFB3303800)
More Information

Abstract

This paper provides a comprehensive review of the current status, advancements, and future prospects of humanoid robots, highlighting their significance in driving the evolution of next-generation industries. By analyzing various research endeavors and key technologies, encompassing ontology structure, control and decision-making, and perception and interaction, a holistic overview of the current state of humanoid robot research is presented. Furthermore, emerging challenges in the field are identified, emphasizing the necessity for a deeper understanding of biological motion mechanisms, improved structural design, enhanced material applications, advanced drive and control methods, and efficient energy utilization. The integration of bionics, brain-inspired intelligence, mechanics, and control is underscored as a promising direction for the development of advanced humanoid robotic systems. This paper serves as an invaluable resource, offering insightful guidance to researchers in the field, while contributing to the ongoing evolution and potential of humanoid robots across diverse domains.

Keywords:

- Future trends and challenges,
- humanoid robots,
- human-robot interaction,
- key technologies,
- potential applications

I. Introduction

HUMANOID robots are meticulously designed machines that closely imitate human appearance and behavior, proficiently replicating functions such as perception, decision-making, and interaction [1]. Inspired by human intelligence and adaptability, these robots have made significant advancements that surpass previous limits. The primary goal is to create humanoid robots capable of ongoing learning and adaptation in unstructured and dynamic environments, ultimately benefiting individuals and propelling the advancement of humanity [2]–[4].

Humanoid robots possess distinct advantages compared to other robot forms. Their human-like design, encompassing torso, arms, and legs, enhances their adaptability to human-centric environments, fostering societal acceptance and enabling complex interactions [5]. This anthropomorphic design facilitates natural human interaction, making them valuable for fields like healthcare and education. Bipedal mobility allows humanoid robots to navigate human spaces efficiently, while their advanced manipulation and dexterity make them capable of intricate tasks [6]. Their cognitive abilities enhance autonomy and adaptability [7]. Moreover, their human safety features, social acceptance, and adaptability to human environments contribute to their suitability for collaborative roles [8]. Despite these advantages, challenges such as balance and energy efficiency persist, making continued research crucial for unlocking their full potential across various domains.

Humanoid robotics, an interdisciplinary field encompassing mechanics, electronics, computer science, artificial intelligence, sensing, and actuation, stands at the forefront of scientific and technological research [9]–[11]. Through progressive research, our comprehension of the structural and functional aspects of humanoid robots has significantly advanced [12], [13]. Pioneering breakthroughs in biomimetic structures, materials, biological information perception, and brain-inspired intelligent control have yielded remarkable experimental applications, showcasing the vast potential of humanoid robots. Nevertheless, a notable disparity remains between the current functional capabilities of humanoid robots and the intricate capacities exhibited by humans [14], [15].

Furthermore, humanoid robots serve as prominent symbols of a nation’s technological capabilities and innovative prowess, owing to the intricate mechanical and electronic components they embody [16]–[20]. Significant progress has been made in enabling these robots to navigate bipedally in diverse environments, demonstrating their adaptability and versatility [21]. The design and control processes of humanoid robots have received significant attention, leading to rapid advancements in motion planning, robot vision, and behavioral control through the implementation of learning algorithms [22]–[24]. However, achieving highly intelligent and versatile humanoid robots remains a formidable challenge in the fields of robotics and artificial intelligence. Unleashing their full potential requires further breakthroughs in both hardware and software domains [25]–[27].

Despite persistent challenges, humanoid robots hold extensive potential for applications across various domains of human life, including military operations, industry, rescue missions, healthcare, education, assistance, entertainment, and agriculture [28], [29]. Their widespread utilization drives the development of next-generation industries and expands the scope of robotic applications, encompassing areas such as national defense, intelligent manufacturing, and social services. Looking ahead, humanoid robots are poised to assume a prominent role in daily life applications, emerging as one of the most significant forms of intelligent robots [30].

Humanoid robots have reached the apex of technological innovation, propelling the advancement and evolution of next-generation industries. This comprehensive paper provides an in-depth review of the current status, advancements, and future prospects of humanoid robots, encompassing key technologies and research endeavors. By addressing emerging challenges and emphasizing the integration of bionics, brain-inspired intelligence, mechanics, and control, the paper serves as a valuable resource for researchers and practitioners. It contributes to the continuous evolution and potential of humanoid robots in diverse domains, fostering interdisciplinary integration and propelling advancements in various fields such as bionics, artificial intelligence, computer science, and material science. Ultimately, this review informs future development and planning, promoting the integration of disciplines for the next generation of humanoid robotic systems.

The paper is organized as follows: Section I introduces the review. Sections II−V delve into different facets of humanoid robots, including research overview, structure and mechanism, control and learning, and perception and interaction. Section VI is dedicated to exploring potential applications of humanoid robots. Section VII delves into future trends and challenges within the field. Section VIII provides a comprehensive conclusion. The main contributions of the paper can be summarized as follows.

1) This paper provides a comprehensive overview of the current state, advancements, and future prospects of humanoid robots, imparting a holistic understanding of this domain.

2) This paper thoroughly investigates fundamental aspects of humanoid robot technology encompassing ontology structure, control, learning, and perception, with the aim of advancing broader research in the field.

3) This paper highlights the potential applications of humanoid robots, emphasizing their adaptability and potential integration into human life.

4) This paper outlines future trends and challenges in humanoid robot research, providing guidance through research directions and challenges for development and utilization.

II. Overview of Humanoid Robot Research

This section presents a comprehensive overview of the research on humanoid robots, including historical advancements and an analysis of the current research status in the field.

A Historical Progression of Humanoid Robots

The exploration of humanoid robots began in the 1970s and gained significant momentum in the early 21st century. They progressed from imitating human appearance and basic movements to evolving into intelligent systems with human-like attributes. This evolutionary progression unfurls through three discrete developmental stages, as depicted in Fig. 1.

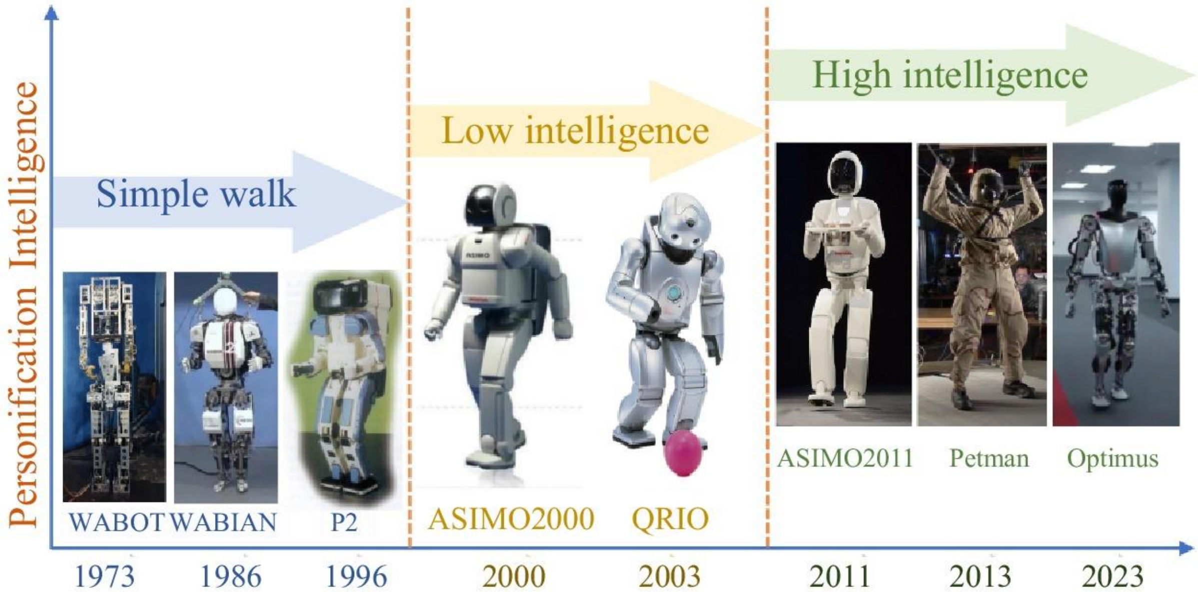


Figure 1. Historical progression of humanoid robots.

DownLoad: Full-Size Img PowerPoint

The initial stage, commencing in the late 1960s, witnessed the nascent advancement of humanoid robots, exemplified by the bipedal walking robots pioneered by Waseda University. This institution spearheaded the research in this domain, and their series of robots, including WAP (Waseda Automatic Pedipulator), WL (Waseda Legged), WABIAN (WAseda BIpedal humANoid), and WABOT (WAseda roBOT), successfully accomplished fundamental walking functionalities [9]. Concurrently, research institutions in Japan, the United States, the European Union, and South Korea also ventured into the field of humanoid robotics, attaining substantial advancements. Throughout this period, the primary emphasis lay in realizing bipedal walking functionality and establishing a foundational level of control [31]–[34].

The second stage of humanoid robots marked a significant advancement with the introduction of highly integrated systems, exemplified by Honda's humanoid robots. During the 21st century, the integration of sensing and intelligent control technologies enabled these robots to possess rudimentary sensory systems, allowing them to perceive basic information from their surroundings. Leveraging these sensory inputs, they demonstrated the ability to make simple judgments and adjust their movements accordingly, leading to smoother and continuous locomotion. A prominent example of this stage was Honda's humanoid robot "ASIMO2000", unveiled in 2000, which not only resembled humans but also showcased predictive capabilities by anticipating future movements and proactively adjusting its center of gravity. This innovation allowed for seamless walking during turns, making ASIMO2000 the first globally influential humanoid robot [35]. Other notable robots from this era include Sony's "QRIO" [36], which debuted in 2003 as the first humanoid robot capable of running, as well as "BIP2000" [37] from France, Sony's "SDR" series [38], and South Korea's "HUBO" [39]. These robots exhibited impressive capabilities such as standing, navigating stairs, running, and engaging in physical exercises.

The third stage showcases breakthrough progress in humanoid robot development, with Boston Dynamics and Tesla leading the way in achieving highly dynamic motion. Advancements in control theory and technology have boosted their cognitive capabilities, enabling them to perform intricate movements independently and with stability. These robots can make informed decisions based on their judgment and surroundings. For instance, Honda's ASIMO robot can perform delicate tasks like grasping objects and pouring liquids accurately by integrating visual and tactile object recognition technologies. It can also respond to voice commands and gestures [40]. Boston Dynamics' ATLAS robot showcases human-like perception, judgment, and decision-making skills, demonstrating dynamic abilities such as navigating conveyor belts, avoiding obstacles, and maintaining balance even in challenging scenarios [41]–[43]. "Petman", another creation by Boston Dynamics, mimics human physiology by regulating body temperature and perspiration [44], [45]. Tesla's humanoid robot, "Optimus prime", is anticipated to revolutionize mass production and contribute to the industrial progress of humanoid robotics [46]. These breakthroughs signify a remarkable advancement, holding promising potential for further strides in intelligent robots capable of intricate tasks.

The entry of renowned companies like Tesla into humanoid robotics highlights the significance of established innovators venturing into new technology areas. Such companies bring attention, funding, and talent, crucial for capital-intensive fields like robotics. Academia contributes by laying theoretical foundations, conducting early research, and fostering innovative ideas. Ideally, collaboration between academia and industry is essential, with academia providing information for industrial applications, and industry offering real-world challenges and data. Humanoid robot development is interdisciplinary, necessitating a diverse ecosystem [47]. Ethical and regulatory considerations become crucial as robots integrate into society, with academia leading discussions, and the industry implementing responsible practices. Ultimately, the trajectory of humanoid robot development depends on market demand and the ability to meet real-world needs. In summary, both academia and industry have vital roles to play, with academia focusing on research, ethics, and long-term planning, while industry drives practical applications and scalability. Effective collaboration is key to unlocking the potential of humanoid robots and advanced technologies.

B Research Ideas of Humanoid Robots

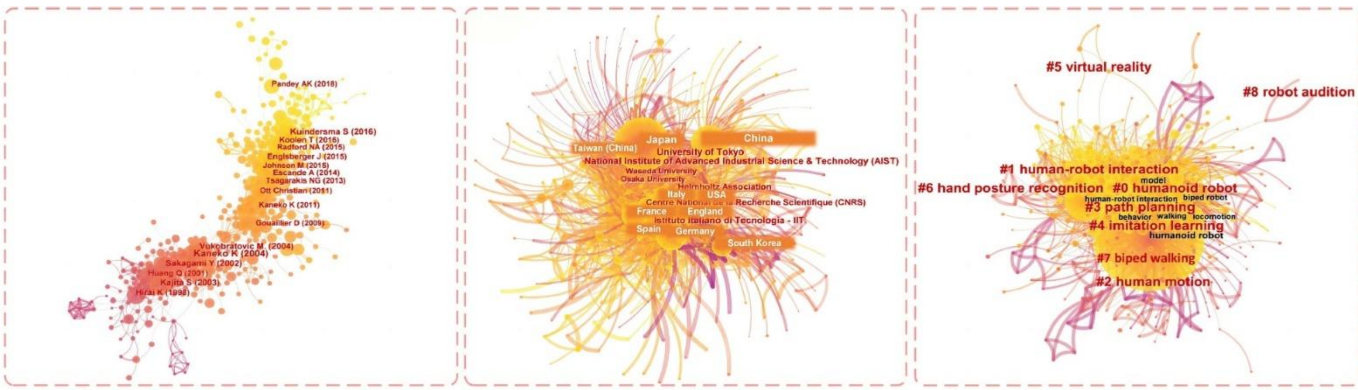
Humanoid robots are currently advancing in two main directions: One aims for a human-like appearance, while the other emphasizes functional similarity, encompassing human-like movements, dexterity, and environmental perception. These approaches stem from different research perspectives and have shaped the field in distinct ways [48], [49].

The first approach focuses on replicating human appearance and functions externally. Through assimilating insights from human behavior, robots acquire the capacity to execute tasks in a manner akin to humans, harnessing sophisticated sensors and adept control programs [40], [42], [50], [51]. Examples of notable research outcomes include Honda's ASIMO robot [40], Beijing Institute of Technology's BHR robot [50], the iCub robot developed by the Italian Institute of Technology [51], [52], and Boston Dynamics' Atlas robot [42]. These robots integrate artificial intelligence algorithms for initial self-learning and adaptability. Through redundant actuators, researchers creating humanoid robots with human-like dexterity though controller design remains a challenge. Various mathematical algorithms have been proposed to control humanoid robots with highly redundant actuators, such as the zero moment point [53], capture point [54], [55], and central pattern generator algorithms [56] for achieving stable bipedal locomotion, as well as model-free reinforcement learning [57] and demonstration-based imitation learning algorithms [58] for diverse operations. While these approaches are still in the early stages of research, they hold promise in expanding the application range of humanoid robots.

The second approach delves into internally emulating core human mechanisms, resulting in intelligent robots with human-like internals. These robots simulate human traits such as visual cognition, decision-making, motor control, and musculoskeletal systems, aiming to establish empathy and deep cooperation with human partners [48]. Research teams globally, including the USA, EU, Japan, South Korea, Canada, Australia, and China, have made significant strides in humanoid mechanisms, brain-inspired algorithms, neuromorphic chips, and musculoskeletal systems, achieving notable progress [59]–[61].

C Research Subjects and Hotspots of Humanoid Robots

A search for “humanoid robots” in the Web of Science database using the time frame 1900−2022 yielded a total of 17 488 relevant papers. After filtering out irrelevant papers, the top 10 000 papers were ranked and analyzed for relevance using citespace, a specialized software for literature analysis. Fig. 2 presents the current research themes and hotspots in the field of humanoid robots, with the



(a) (b) (c)

results visualized as follows:

Figure 2. The mapping knowledge domain of humanoid robots. (a) Co-citation analysis; (b) Country and institution analysis; (c) Cluster analysis of keywords.

DownLoad: Full-Size Img PowerPoint

1) Co-Citation Analysis: Examining the distribution of authors in the literature, it is evident that early research on humanoid robots was pioneered by authors like K. Hirai, S. Kajita, and Q. Huang. In recent years, an increasing number of researchers, including prominent figures like S. Kuindersma and K. Kaneko, have joined the field and contributed to humanoid robot research.

2) Country and Institution Analysis: The analysis of author-country clusters reveals that the major research countries of humanoid robots are Japan, USA, and China. Key research institutions include the University of Tokyo, Waseda University, and Osaka University in Japan, Beijing Institute of Technology and

Tsinghua University in China, and the Massachusetts Institute of Technology in USA. Other countries, such as Italy, Germany, France, the UK, and South Korea, have also made significant contributions to related research.

3) Cluster Analysis of Keyword: Analyzing the distribution of keywords in the papers, it is observed that research on humanoid robots primarily focuses on topics such as human-robot interaction, human motion, path planning, imitation learning, biped walking, virtual reality, and hand posture recognition.

As shown in Fig. 3, the number of papers on humanoid robotics demonstrated a steady increase from 1998 to 2011, reflecting a growing interest in the field. Since 2012, there has been a substantial surge in research, driven by technological advancements, the robotics competition, media coverage, practical applications, increased funding, collaboration, and academic interest. This surge led to a peak of over 1000 papers published annually from 2014 to 2022, indicating a persistent and enthusiastic trend in humanoid robot research over the past decade.

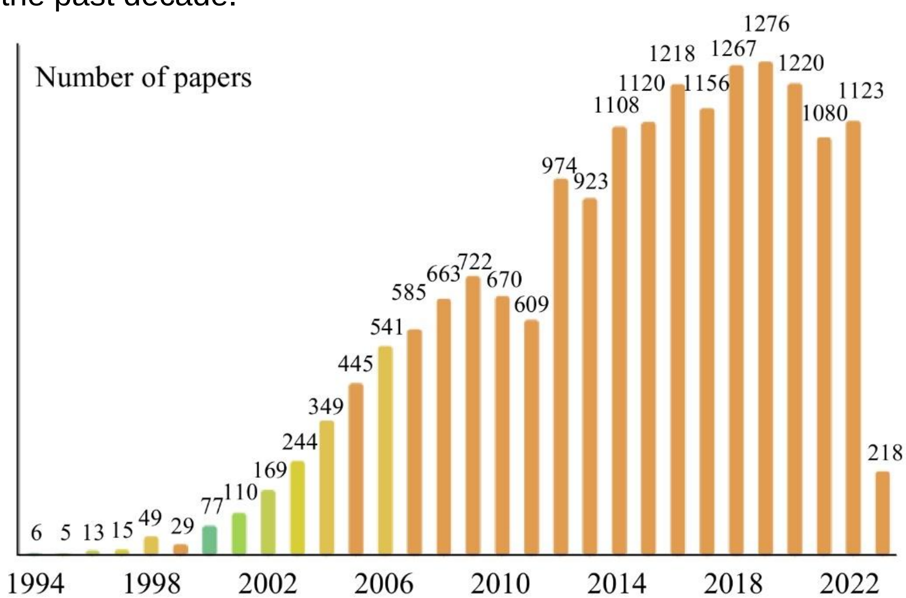


Figure 3. The number of papers varies with each year.

DownLoad: Full-Size Img PowerPoint

D Research Status of Humanoid Robots

Various countries have designed unique humanoid robots, each characterized by specific attributes and abilities, as illustrated in Fig. 4. Table I provides a comprehensive overview of the progress and achievements in humanoid robot research by highlighting a selection of representative models. This table summarizes the advancements made in humanoid robots, particularly in areas such as movement, dexterity, interaction, and cognitive capabilities.

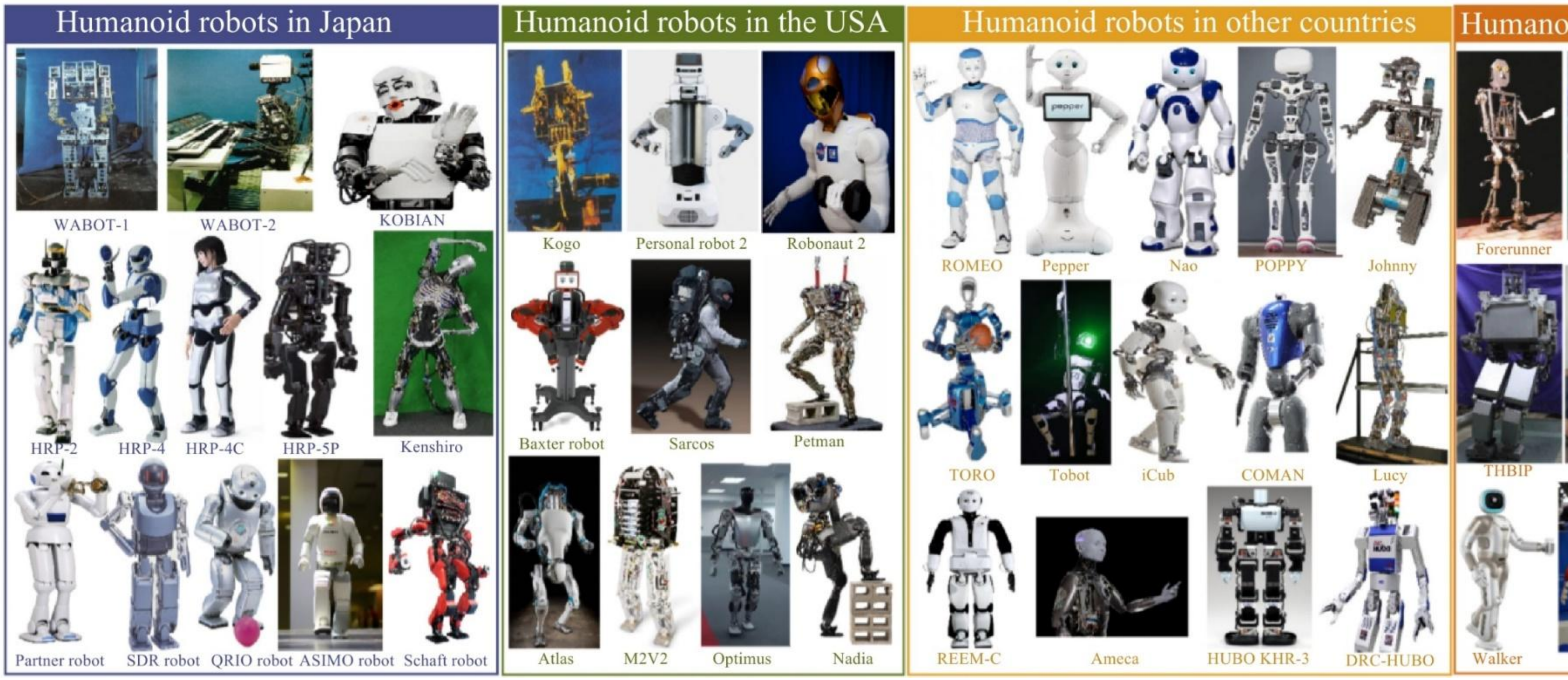


Figure 4. Research status of humanoid robots

DownLoad: Full-Size Img PowerPoint

Table I. Performance Parameters of Some Typical Humanoid Robots

Robot	Year	Research institute	DOF	Mass (kg)	Height (m)	Mobility	Passive joints
WABIAN-2 [65]	2005	Waseda University, Japan	41	64.5	1.53	Biped	No
Twendy-One [99]	2007	Waseda University, Japan	47	111	1.47	Wheeled	Yes
H7 [100]	2001	JSK, Japan	30	57	1.46	Biped	No
Kengoro [101]	2016	JSK, Japan	68	56	1.7	Biped	Yes
HRP-2 [66]	2004	AIST, Japan	30	58	1.54	Biped	No

Robot	Year	Research institute	DOF	Mass (kg)	Height (m)	Mobility	Passive joints
HRP-4C [68]	2009	AIST, Japan	42	43	1.58	Biped	No
ASIMO2011 [40], [76]	2011	Honda Giken, Japan	57	48	1.3	Biped	No
HUMANOID [102]	2005	Toyota, Japan	31	40	1.48	Biped	No
HERB [103]	2012	CMU, USA	2×7	–	–	Wheeled	Yes
Robonaut 2 [82], [85]	2010	NASA, USA	58	223	2.4	Biped	Yes
Valkyrie [104]	2013	NASA, USA	44	44	1.9	Biped	Yes
PR2 [81]	2010	Willow Garage, USA	2×7	–	1.26	Wheeled	Yes
Meka M1 [105]	2011	Meka Robotics, USA	2×7	165	1.75	Wheeled	Yes
ATLAS [41]	2016	Boston Dynamics, USA	28	82	1.65	Biped	No
Optimus Prime	2023	Tesla, USA	40	56	1.73	Biped	Yes
iCub [51], [52], [106]	2004	IIT, Italy	53	25	1.04	Biped	No
WALK-MAN [107]	2013	IIT, Italy	33	120	1.85	Biped	No
COMAN [108], [109]	2015	IIT, Italy	25	31	0.95	Biped	Yes
Justin [110]	2007	DLR, Germany	43	45	1.7	Wheeled	No
ARMAR-IV [111]	2013	KIT, Germany	63	70	1.7	Biped	Yes
RoboThes-pian [112]	2007	Engineered Arts, UK	30	33	1.75	Fixed	No

Robot	Year	Research institute	DOF	Mass (kg)	Height (m)	Mobility	Passive joints
REEM-C [113], [114]	2014	Pal Robotics, Spain	68	70	1.6	Biped	No
Pepper [115]–[117]	2012	Aldebaran, France	20	28	1.28	Wheeled	No
ROMEO [118]–[120]	2012	Aldebaran, France	37	44	1.4	Biped	Yes
Albert-HUBO [39]	2006	KAIST South Korea	66	57	1.37	Biped	No
DRC-HUBO [121]	2015	KAIST South Korea	33	80	1.75	Biped/Wheeled	No
Blackman	2005	NUDT, China	36	63.5	1.54	Biped	No
BRH-5 [122]	2012	BIT, China	30	63	1.62	Biped	No
Wu Kong [123], [124]	2011	ZJU, China	30	55	1.62	Biped	No
GOROBOT-II [50]	2005	HIT, China	25	35	1.7	Biped/Wheeled	No
GOROBOT-III [50]	2007	HIT, China	70	90	1.58	Biped	No
THBIP-I [125]	2002	THU, China	32	130	1.8	Biped	No
DARwIn-OP [126]	2011	UTokyo, Japan	20	2.8	0.45	Biped	No
NAO [127]	2009	Aldebaran, France	25	4.5	0.57	Biped	No
Poppy [128], [129]	2014	INRIA, France	25	3.5	0.83	Biped	Yes
Igus [130]	2015	AIS, Germany	20	6.6	0.92	Biped	No
ARC [131]	2018	University of Tabriz, Iran	20	2.9	0.54	Biped	No

Robot	Year	Research institute	DOF	Mass (kg)	Height (m)	Mobility	Passive joints
Surena-Mini [132]	2017	CAST, Iran	23	3.3	0.53	Biped	No
NimbRo-OP2 [133], [134]	2018	AIS, Germany	20	19	1.35	Biped	No
Lola [135]	2009	TUM, Germany	25	55	1.8	Biped	No

| Show Table

DownLoad: CSV

1) Humanoid Robots in Japan: Research on humanoid robots in Japan has predominantly focused on morphological simulation, with a specific emphasis on developing intricate and lifelike bionic robots tailored towards domestic and service-oriented applications [62].

Waseda University pioneered humanoid robot development with the groundbreaking WABOT series in 1976, achieving the first successful implementation of bipedal walking technology [63], [64]. Over nearly five decades, Waseda University has sustained its leadership in advancing humanoid robotics. Collaborating with the National Institute of advanced industrial science and technology (AIST), the university's contributions extended to the WABIAN series, enriching the domains of bipedal locomotion, control algorithms, and the intricate interplay between humans and robots [65]. The AIST catalyzed significant progress in the realm of humanoid robotics, exemplified by the HRP line of robots [66]. These platforms have illuminated diverse avenues of research encompassing humanoid locomotion, manipulation, and human-robot interaction. Notably, the HRP-4 robot emerged as a striking testament to its ability to mimic human movements and manipulations [67]. Subsequent iterations like the HRP-4C [68] optimized motor skills and expressions, while the HRP-5P [69] fortified stability against external forces. Additionally, the University of Tokyo's Kenshiro humanoid robot demonstrated enhanced flexibility through an increased number of degrees of freedom [70]–[72].

Aside from research institutions, notable companies such as Honda, Toyota, and Sony have made significant contributions to humanoid robot research [35], [73]–

[75]. Honda's partner robot (PR) achieved high-speed running capabilities through a unique design inspired by horse hooves. Sony developed entertaining humanoid robots, namely the SDR and QRIO, capable of singing, dancing, kicking a ball, and engaging in human-computer interaction [36]. ASIMO, Honda's renowned robot introduced in 2000, represents a reduction in size from the P2 humanoid walking robot while further enhancing walking and working capabilities. The improved version of ASIMO, developed in 2011, demonstrated the ability to walk on uneven surfaces, perform voice recognition, avoid static and moving obstacles, and exhibit multi-finger coordination [40], [76]–[80]. Another noteworthy creation is the Schaft robot, developed in 2013, which exhibits the capacity to navigate uneven terrains and climb ladders, among other functions [62].

2) Humanoid Robots in the USA: In the USA, humanoid robotics research has primarily focused on understanding the mechanisms and functional simulation of the human brain, resulting in significant advancements in operating robots within complex environments. These achievements lay a solid foundation for potential real-world applications.

One notable institution, the MIT LegLab, adopted a progressive approach from the 1980s to the 1990s, culminating in the development of a series of highly capable mobile humanoid robots based on pneumatic telescopic leg mechanisms. These robots demonstrated remarkable locomotor capabilities due to the high power density of pneumatic mechanisms. For instance, the planar biped and the 3D biped not only exhibited fast running speeds but also performed cartwheels while in motion [31]–[34]. The MIT Artificial Intelligence Laboratory contributed to the field with the Kogo robot, which emulated human-like learning processes to perform specific tasks. Additionally, Willow Garage's two-armed service robot, PR2 (personal robot 2), showcased the ability to execute complex operations such as folding clothes and towels, opening doors, and autonomously locating its own charging socket [81]. NASA developed the humanoid two-armed robot, Robonaut 2, which replaced astronauts during tests on the international space station, carrying out repetitive tasks in the hazardous space environment [82]–[86]. Agility robotics is a leading company known for innovative humanoid robots, like their flagship "Cassie" humanoid robot and "Digit" humanoid robot, which sets new standards in versatile robotic mobility [87], [88]. Rethink Robotics introduced the Baxter robot, a new generation of flexible two-armed industrial robots. Baxter robots are known for their cost-effectiveness, versatility, and ease of programming, making them suitable for a wide range of applications [89]–[92]. Sarcos developed the Sarcos humanoid robot capable of maintaining balance and achieving movement despite disturbances during walking and standing. Boston dynamics, a renowned leader in humanoid robotics, has developed a variety of dynamic and highly mobile robots. The original humanoid robot, Petman, was designed to perform actions such as walking, push-ups, and overcoming obstacles [45]. Building upon Petman, the Atlas robot underwent comprehensive improvements in walking and manipulation capabilities, enabling it to operate in unknown environments [41]–[43]. The institute for human and machine cognition (IHMC) stands as a prominent research institute specializing in humanoid robot walking motion control. In 2019, IHMC designed and developed the M2V2 humanoid robot specifically for urban environments [93], [94]. Tesla unveiled its latest humanoid robot, Optimus Prime, in 2022, envisioning its deployment in thousands of households. Optimus Prime demonstrates human-like dexterity, steady walking, the ability to bend over, wave to audiences, and perform simple dance moves [46], [95]. Additionally, Nadia, jointly designed and built by IHMC and Boardwalk Robotics, represents the next generation of humanoid robots. It possesses a wide range of motion, high speed, and great strength. With experience gained from working with robots such as Boston Dynamics' Atlas and NASA's Valkyrie, Nadia aims to advance robotics and apply these technologies to practical real-world applications. Unlike Tesla's Optimus Prime, Nadia employs a hybrid power system, combining electric and hydraulic power sources [96]–[98].

3) Humanoid Robots in Other Countries: In various countries, the research on humanoid robots has been influenced and inspired by the distinctive studies conducted in the USA and Japan, leading to further innovative research and development.

In France, Aldebaran Robotics has made significant contributions to humanoid robotics with the development of various humanoid robots, including ROMEO, Pepper, and NAO. The NAO robot, widely utilized in the academic field, has gained global recognition [127]. ROMEO, primarily designed for personal care, possesses the ability to observe its surroundings and engage in conversations with humans [118]–[120]. The Pepper robot is designed to interact with humans, specifically, recognizing emotions through human facial expressions and voices and adapting conversational patterns accordingly [115]–[117]. The Flower Lab at Inria has developed POPPY, a low-cost humanoid robot manufactured using 3D printing technology. POPPY's movements closely resemble those of a human [128], [129]. Germany, specifically the Technical University of Munich, has developed the Johnny humanoid robot, primarily utilized for kinematic research, indoor environmental services, and fast walking, including navigating obstacles [136], [137]. The German Aerospace Center (DLR) has developed the TORO humanoid robot, which emphasizes coordinated control of the robot's arms and gait control for safe human-robot interaction [138], [139]. Tobot, a software company, has created two robots capable of dancing to music. The iCub humanoid robot, developed by the Italian Institute of Technology, plays a significant role in human cognition and artificial intelligence research, aimed to deepen our understanding of human cognitive processes [51], [52], [106], [140]. Additionally, the Italian Engineering School has developed the flexible humanoid robot COMAN, primarily for studying the planning and control of natural walking and jumping movements [108], [109], [141], [142]. The University of Brussels in Belgium has developed the Lucy humanoid robot, equipped with pneumatic artificial muscles [143]. PAL in Spain has introduced the REEM-C humanoid robot, featuring walking, visual recognition, and human-robot interaction capabilities [113], [114]. Engineered Arts, a British Technology Company, has created a humanoid robot, renowned for its realistic expressions and advanced interaction capabilities, earning it the reputation of being one of the most human-like robots [112]. In South Korea, the KHR series of humanoid robots developed by KAIST enjoys significant recognition [144], [145]. The HUBO KHR-3 robot can walk at a speed of 1.4 km/h with a straight-knee gait and run at 3.6 km/h [146]. The DRC-HUBO robot employs an innovative wheel-leg combination model to enhance stability in uncertain environments [39], [121], [147].

4) Humanoid Robots in China: China has made significant progress in the field of humanoid robots, with various universities and research institutes leading the way. Some notable achievements include the development of the “Forerunner” in 2000 by the National University of Defence Technology, and the “BHR” humanoid robot in 2002 by the Beijing Institute of Technology, which showcased stable walking on unknown terrain and complex movements [148]. Other institutions, like the Harbin Institute of Technology [149] and Tsinghua University [125], [150], also contributed with successful bipedal walking robots and unique transmission structures for stable walking. Peking University's "Runbo" humanoid robot employed an elastic mechanism for smooth walking and agile task performance [151], [152]. The Beijing Institute of Technology's five generations of the BHR series robots are considered representative humanoid robots in China, with the "GOROBOT 5" achieving breakthroughs in motion control and autonomous response based on high-speed vision [122]. Zhejiang University excelled in high-speed vision perception, dexterous motion planning, and precise balance control, even developing humanoid robots for table tennis and football [123], [124]. Chinese companies have advanced in humanoid robot development, with notable examples including Ubtech's Alpha robot in 2015, the Walker humanoid service robot in 2021, and Xiaomi's CyberOne in 2022, China's first full-size bionic humanoid robot with advanced features [48], [49]. These advancements in China's humanoid robotics reflect the country's expertise and dedication to exploring the potential applications of humanoid robots across various domains.

III. Ontological Structure & Modules

This section summarizes the ontology structure and mechanism of humanoid robots, including a discussion of the various modules involved.

A Mechanical Design

The mechanical design of humanoid robots is of utmost significance, drawing inspiration from the intricate structure and subtle motions of the human body [153]–[155]. This design serves a dual role, facilitating practical interactions while also providing a platform for scholarly exploration into bipedal locomotion and associated research pursuits [20], [69], [156]. Comprehensive comparisons of specifications in Tables I and II offer insights into various humanoid robots, facilitating understanding of their capabilities. Parameters such as degrees of freedom, weight, size, power supply, and sensors shed light on strengths and limitations, aiding researchers and developers. This analysis reveals trends and progress in humanoid robotics, supporting further research. The implementation of techniques such as laser cutting, CNC machining, and 3D printing contributes to the construction of intricate mechanical frameworks, wherein the latter emerges as a transformative innovation, offering an array of cost-effective prospects for crafting lightweight and structurally economical frameworks [69], [155], [157], [158]. A notable trajectory in this domain involves the impetus of commercial enterprises towards the development of lightweight and open platform humanoid robots, exemplified by noteworthy entities such as DARwIn-OP [126], Open-HRP [130], [133], [134], Aldebaran Nao [127], iCub [52], [106], and NimbRo-OP [130], [133].

Table II. Ontological Structure and Modules of Some Typical Humanoid Robots

Robot	Structure material	Actuators type	Processing unit	Sensors
DARwIn-OP [126]	Aluminum, plastic	Electrical	Atom Z530 1.6 GHz CPU (32 bit) on-board 4 GB flash SSD	Camera, IMU
NAO [127]	ABS	Electrical	ATOM Z530 1.6 GHz CPU, 1 GB RAM2, 2 GB Flash memory, 8 GB Micro SDHC	Camera, IMU, force, sensitive resistors, sonar, rotary, encoders, tactile
Poppy [128], [129]	Plastics, aluminum	Electrical	Raspberry Pi	Stereo micros, force, IMU
Igus [130]	Iglidur, polymer	Electrical	Intel i7, 2.4 GHz CPU 4 GB RAM, 120 GB SSD	Camera, IMU, encoders
iCub [51], [52], [106]	Aluminum, titanium	Electrical	Microcontroller based Freescale 56F807 chip	Cameras, IMU, force, torque, microphone
ARC [131]	Aluminum, titanium	Electrical	Intel i5, 1.8 GHz CPU 32 GB RAM	–
Surena mini [132]	Aluminum, titanium, CFRP	Electrical	Intel core m5, 1.1 GHz CPU, 4 GB DDR3, 64 GB eMMC	Camera, microphone, force, IMU, IR, touche, encoder
ASIMO [40], [76]	Magnesium alloy	Electrical, hydraulic	Pentium II-M 1.2 GHz	Camera, IMU, force, microphone, tactile
NimbRo-OP2 [133], [134]	Aluminum, plastics	Electrical	Intel i7 2.4 GHz CPU 4 GB RAM 120 GB SSD	Camera, IMU, encoders

Robot	Structure material	Actuators type	Processing unit	Sensors
HRP-4 [67]	Aluminum, magnesium	Electrical	Intel Pentium M 1.6 GHz	Camera, IMU, force
REEM-C [113], [114]	Aluminum	Electrical	Intel core i7 2.4 GHz	Camera, sonar, laser scanner, force, torque, IMU
Atlas [41]	Aluminum, titanium	Hydraulic	–	Camera, lidar
HUBO+ [39], [121]	Frubber, metal	Electrical	Intel Atom 1.6 GHz	Camera, force, torque, inclinometer, IMU
Lola [135]	Aluminum	Electrical	Intel Core Duo 2.33 GHz	Camera, force, torque, joint, IMU

| Show Table

DownLoad: CSV

B Classification of Humanoid Robots

Within the domain of humanoid robotics, a categorization predicated on scale delineates differences between adult-sized and child-sized iterations. Adult-sized humanoid robots, typically exceeding one meter in height and equipped with bipedal locomotion, embody a diverse array of attributes encompassing advanced control systems, sophisticated planning capabilities, intricate mechatronics, comprehensive AI sensing technologies, optimal mobility and working range, and refined human-robot interaction capabilities. Conversely, child-sized humanoid robots, epitomized by models such as NAO and Alpha, materialize as tabletop entities tailored for specific scales and applications, characterized by a compact form factor conducive to tabletop interactions. Table III delves into an analytical examination of the characteristics and application scenarios associated with these two distinct categories of humanoid robots. It offers an insightful breakdown of the key differentiating factors, shedding light on the specific strengths and development prospects of adult-sized and child-sized humanoid robots. Additionally, Fig. 5 visually supplements this examination by illustrating system complexity, energy consumption, functionality, interaction capability, load capacity, and the volume-to-mass ratio, enabling an comprehensive and intuitive comparison of performance attributes across varying sizes. The boundaries of these areas in the diagram are based on the performance statistics of various types of humanoid robots of different sizes derived from a comprehensive review of existing research in the field. By elucidating these factors, researchers and developers can gain a deeper understanding of the performance distinctions between the two sizes of humanoid robots, enabling informed decision-making in accordance with their specific requirements and objectives.

Table III. Classification of Humanoid Robots

Size	Child size	Adult size
Representative	DARwIn-OP, ROBOTIS-OP3, NAO, Poppy, Igus, iCub, ARC, Surena mini	ASIMO, NimbRo-OP2, HRP-4, REEM-C, Atlas, HUBO+, Lola
Advantage	Simple structural design; Lightweight; Low energy consumption; Cost-controlled; Relatively simple control system.	Strong interactive ability; Strong versatility; Large load capacity.
Disadvantage	Basically in situ motion control only; Limited interaction capability; Small load capacity.	Complex structural design; Heavy mass; Complex control system; High cost.
Application	Low load, small size range, low power consumption application scenarios.	Large-load, cross-domain, multi-tasking application scenarios.

| Show Table

DownLoad: CSV

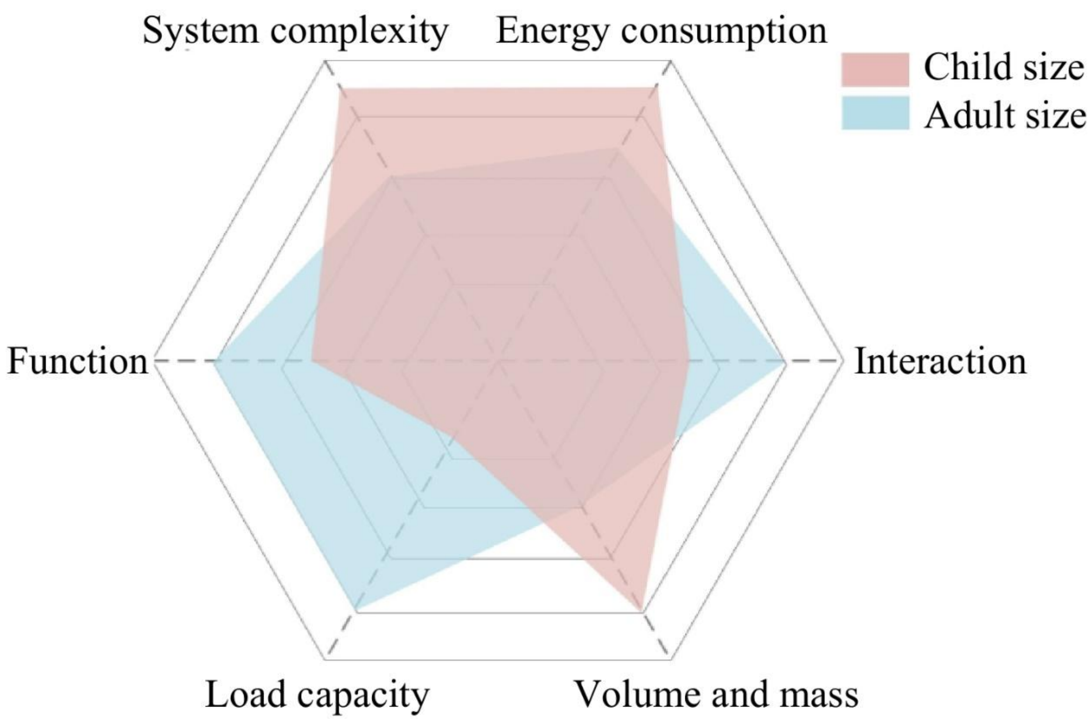


Figure 5. Comparison of Child-size and Adult-size humanoid robots

DownLoad: Full-Size Img PowerPoint

C Kinematics, Dynamics and Biomechanics

The intricate complexities intrinsic to humanoid robots, characterized by their elevated order, intricate interconnections, and non-linear attributes, present challenges when it comes to precisely addressing the intricacies of kinematics and dynamics. Furthermore, the absence of fixed reference points and the potential for collisions during their motion introduce additional layers of complexity [25], [26]. Classical methodologies, exemplified by the venerable Lagrange and Newton-Euler equations, find themselves constrained by the intricate tapestry that envelops these robotic systems. Analytical solutions for inverse kinematics, reliant on constraints to approximate solutions, often yield disparities between the intended trajectory and the realized trajectory. To navigate these intricacies, scholars are delving into alternative avenues, including neural networks, genetic algorithms, and fuzzy logic, with a focus on robustness and computational efficiency [159]–[162]. This infusion of novel paradigms, in harmony with the continuous evolution of computing capabilities, presents pragmatic pathways for effectively addressing the intricate challenges inherent in multi-degree-of-freedom humanoid robots.

D Processing Units

Humanoid robots encompass not only their mechanical structure but also incorporate one or multiple processing units. The selection of electronic components for humanoid robots is generally driven by the specific application requirements, such as autonomy, remote operation, the intended tasks of the robot, and the associated cost considerations. In the present landscape, a wide array of processing units are available for integration into humanoid robots. Over the past decade, advancements in technology have introduced smaller processing units, prompting many humanoid robot developers to opt for diverse and compact processing units, particularly mini PCs, especially in competitive settings [133], [163].

Furthermore, alongside custom-made master boards, commercial master boards are also widely utilized in humanoid robots. Raspberry PI boards [164], ARM-based boards [165], compatible Arduino boards [166], and off-board computing controls [43] are commonly employed in the development of humanoid robots. The information presented in Tables I and II indicates a general trend where an increase in the number of degrees of freedom of a robot corresponds to an increase in its size. Consequently, more powerful processing units and higher power requirements are necessary, leading to elevated costs in the overall system.

IV. Control, Drive & Decision Making

Compared to human capabilities, there’s a noticeable gap in agility and autonomy in humanoid robots [167], which this section addresses by discussing control, actuation, and learning methods to achieve desired behaviors.

A Control of Humanoid Robots

1) Categorization of Humanoid Robot Control Methods: This section offers a thorough overview of humanoid robot control method categorization, complemented by Table IV, which summarizes the classification and distinct characteristics of current control methods.

Table IV. Control and Learning of Humanoid Robots

Classification	Example	Characteristic
Traditional method	ZMP-based [168], dynamical model-based [169]	Traditional method allows for stabilization but does not apply to environments where obstacles are present and lack the exploration of optimal control.
Optimization-based method	PSO [170], CFO [171], MPC [172], TO [173]	Optimization-based methods can achieve better gait but are challenging to apply to complex environments.
Model-based method	Balance strategy [174], real-time feedback [175], VGC [176]	Model-based control methods employ dynamic models of robots and their environments to compute optimal control commands, but model applicability is poor.
Bionic method	CMAC [177], CPG [178]	Bionic methods utilize biological properties and can be planned from human control principles, but is dependent on a specific environment.
Reinforcement learning	Model-free [179], model-based [180]	Reinforcement learning starts with a random policy and gradually updates it based on reward feedback from the environment to achieve a specific goal, but the difference between the simulation environment and the actual environment leads to low practicality.
Demonstration learning	BC [181], IRL [182]	Demonstration learning imitates expert behavior that facilitates rapid acquisition of human motor skills, but still presents challenges in terms of strategy generalization, dataset dependency, and simulation-to-real-world transition.

| Show Table

DownLoad: CSV

a) Traditional control methods: The foundation of humanoid robot control rests on traditional control methods, exemplified by the zero moment point (ZMP)-based method [168] and the dynamic model-based method [169]. The ZMP-based approach excels in generating stable gait patterns but faces limitations related to walking speed and robustness. Conversely, the dynamic model-based method offers excellent stability and lower computational complexity, albeit with applicability often confined to idealized flat terrain for modeling and control.

b) Optimization-based control methods: Optimization-based locomotion control methods have revolutionized humanoid robots, allowing precise control of a wide range of movements. By framing challenges as real-time optimization, these methods include techniques like particle swarm optimization (PSO) [170], central force optimization (CFO) [171], model predictive control (MPC) [172], and trajectory optimization (TO) [173]. Whole-body control (WBC) blends upper and lower body tasks, prioritizing task execution while respecting constraints. Recent MPC advancements enhance real-time adaptability and efficiency. Contact planning, terrain adaptability, and balancing strategies optimize interaction with the environment. Distributed control streamlines complex problems, integrating sensors and actuators throughout the robot. Online perception and task hierarchies enhance adaptability, while machine learning refines control in dynamic environments. In conclusion, recent advances in optimization-based motion control for humanoid robots have significantly enhanced their capabilities in terms of balance, adaptability, versatility, and real-time decision-making. These developments pave the way for humanoid robots to perform a broader range of tasks in various environments.

c) Model-based control methods: Model-based control methods employ dynamic models of robots and their environments to compute optimal control commands, ensuring precise and stable movements. The balance strategy method based on human body data [174] enables adaptive strategies to cope with diverse disturbances. The real-time feedback method [175] stabilizes walking while dynamically adjusting gait in real-time, though it may have limitations in transferability. The virtual gravity compensation (VGC) method [176] facilitates stable walking on uneven terrain and in the presence of disturbances.

d) Bionic control methods: Bionic control introduces two significant components: the cerebellum-model-articulation controller (CMAC) [177] and the central pattern generator (CPG) [178]. CMAC distinguishes itself through robustness in handling noise and interference. Conversely, CPG exhibits broad applicability but presents challenges related to parameter tuning.

e) Learning-based control methods: The advent of machine learning and deep reinforcement learning, exemplified by techniques like deep reinforcement learning (DRL), has revolutionized humanoid robot control. These methods empower robots to acquire complex motor skills, adapt to uncertain environments, and enhance locomotion capabilities by learning from data and experience.

2) Advancements in Humanoid Robot Control Domains: The present state of research in control has yielded substantial progress across various domains. This section provides a comprehensive overview of these advancements:

a) Locomotion control: Achieving bipedal locomotion stands as a fundamental challenge in humanoid robotics. Humanoid robots emphasize legged movements, particularly bipedal gait, closely mirroring human walking patterns [50], [183], [184]. They aim for omnidirectional walking adaptable to various speeds and terrains, seeking versatile, dynamic, and dependable locomotion [42], [185], [186]. Controlling omnidirectional walking poses challenges in complex scenarios and harsh environments, and necessitates thorough kinematic analysis and robust walking engine development [20]. Bipedal walking in humanoid robots includes open-loop and closed-loop walking engines [131], making it a prominent research area [187]. Recent research explores simplified algorithms based on robust regression for trajectory tangent estimation and temporal similarity and smoothness optimization. Additionally, MPC, initially designed for autonomous driving, has found application in humanoid robot gait control, regulating centroid position and posture [188], [189]. Researchers also explore diverse locomotion strategies, spanning activities such as walking, running, stair climbing, and traversing rough terrains.

b) Balance and stability control: Minimal energy consumption during ideal motion planning in humanoid robot walking necessitates meticulous consideration of motion balance and stability [187], [190]. Research efforts focus on enhancing balance control through advanced algorithms that integrate various sensory inputs, including inertial measurement units (IMUs) and vision. Various stability criteria apply, including the position of the robot’s center of mass (COM) and center of pressure (COP) within a convex region of foot support, ensuring stability [183], [191]. Quasi-dynamic walking approximates dynamic walking while simplifying dynamics, relying on the concept of zero moment points (ZMP) [184], [192], [193]. ZMP balances computational complexity and stable motion, enhancing energy-efficient locomotion [22]. Progress has been made in dynamic walking, inspired by passive dynamic walking (PDW), optimizing equilibrium stability through probabilistic reinforcement learning and other approaches.

c) Behavior control: Behavioral control poses a pivotal challenge in humanoid robot control, encompassing autonomous, semi-autonomous, and remote control methods [194]. Researchers explore diverse artificial intelligence approaches within autonomous and semi-autonomous behavioral control systems [195]. Complex tasks demand intelligent decision systems, with key research directions including path planning, footprint planning, and navigation for autonomous and semi-autonomous humanoid robots [196]. Navigating complex environments involves addressing self-collision detection, path planning, and obstacle avoidance [195]. Humanoid robots, leveraging their bipedal nature, can overcome obstacles and navigate stairs and ladders in rugged terrains [24], [40], [67], [76]. However, achieving a suitable solution in dynamic environments remains an ongoing pursuit. In the case of remotely controlled robots, complex tasks often demand intricate decision-making systems, leading to remote control approaches.

In addition to these areas, current research developments in other domains are described below: Real-time control in humanoid robots has significantly improved, enabling efficient execution of complex tasks. Control algorithms rapidly process sensory information and adapt to changing environments. Humanoid robots maintain balance even in challenging situations, such as being pushed or on uneven terrain. State-of-the-art control algorithms utilize predictive control strategies to ensure dynamic stability [172], [197], [198]. Research has enhanced humanoid robots' adaptability to unforeseen circumstances. Learning-based approaches enable robots to recover from disturbances and adapt to varying conditions, increasing their versatility [199]–[201]. Control research has expanded to include more complex manipulation tasks [202]. Integration of advanced sensors, including lidar, cameras, and tactile sensors, has heightened the perception and decision-making capabilities of humanoid robots [203]. Control algorithms effectively utilize these sensors for tasks such as object recognition and navigation [204], [205]. Control research extends its purview to enhancing human-robot interaction (HRI), encompassing the development of control algorithms that facilitate natural and secure interactions between robots and humans [206]–[208]. This includes shared workspaces, assistive device scenarios, and collaborative tasks.

B Actuators of Humanoid Robots

Humanoid robots are meticulously designed to replicate the intricate structure of the human body, allowing their actuators to emulate human muscles and joints, thereby enabling lifelike movements [209]. Actuators in humanoid robots are categorized into various types, each with distinct pros and cons that influence the robot's performance, efficiency, and design intricacies.

Electric actuators, encompassing both brushed and brushless DC motors, impart precise control, robust torque, and efficient energy utilization within compact dimensions. Their ability to recapture energy during deceleration is noteworthy. Yet, their potential heftiness necessitates sophisticated control strategies for versatile motion [121]. Pneumatic actuators, exemplified by muscular mechanisms, imbue the robot with lightweight and adaptable motion, characterized by heightened force-to-weight ratios. However, their reliance on a continuous supply of compressed air incurs a trade-off in energy efficiency [165]. Hydraulic actuators excel in demanding tasks and dynamic maneuvers, surpassing specific pneumatic counterparts in terms of efficiency. Notwithstanding their prowess, hydraulic actuators exhibit dimensions that can be substantial, necessitate hydraulic fluid, and involve intricate control paradigms [121], [210]. Shape memory alloys (SMAs) introduce an avenue for lightweight and noiseless actuation, albeit with restricted force and response time capabilities, thereby necessitating intermittent cooling intervals. Cable-driven actuators facilitate expansive and agile motion, albeit entailing intricate kinematics and considerations regarding friction. Compliant actuators, typified by series elastic actuators (SEAs), ensure safety and energy storage attributes, despite potentially incurring minor trade-offs in accuracy and efficiency when juxtaposed with rigid alternatives [154].

Selecting actuators hinges on specific application, performance requisites, weight constraints, safety concerns, and desired complexity level. Designers often navigate trade-offs to achieve an optimal equilibrium between factors like precision, force, efficiency and adaptability [164], [211].

C Learning of Humanoid Robots

Humanoid robots strive to imitate human thinking and behavior. They learn from their surroundings, autonomously perform various tasks, and adapt to different environments, whether planned or unpredictable [212]–[214]. For a comprehensive overview, Table IV summarizes the classification and distinct characteristics of current learning methods for humanoid robots.

1) Reinforcement Learning (RL): RL is a decision-making paradigm that models problems as a Markov decision processes (MDP). In RL, the agent initially employs a random policy and iteratively updates it based on reward feedback from the environment to achieve specific goals [215], [216]. Traditional RL methods, such as Q-learning [217], [218] and policy gradients [53], have been successfully applied to gait control in humanoid robots. Furthermore, the advent of DRL, which combines the decision-making capabilities of RL with the perceptual capabilities of deep learning, has significantly expanded the application of RL in robotics [219].

RL can be classified into two types: Model-based and model-free, depending on whether the state transition probabilities and rewards are known. Model-free RL methods optimize policies through iterative interactions with the environment, learning through trial and error [220]. Two major types of model-free RL algorithms, namely value-based and policy-based, have been employed in various studies [179], [221]–[223]. Model-based RL methods [180], [224] learn to simulate the environment using models and receive feedback. By utilizing learned environments, exploration and policy search can be guided, resulting in lower sample requirements and higher efficiency [224]. The model-free approach enables agents to directly learn from robot experience, but necessitates re-exploration when the task or environment changes. On the other hand, the model-based approach requires less exploration and exhibits strong generalization capabilities, but the acquisition and learning of the model itself is challenging. Consequently, some researchers strive to combine these two methods to complement each other [225]–[227].

However, conducting RL solely through trial and error in the real environment is not only perilous but also inefficient. Transfer learning from simulation to the real world introduces challenges in the sim-to-real transfer [228].

2) Demonstration Learning: Demonstration learning is a prevalent method in humanoid robotics for swift acquisition of human skills [229]–[231]. This approach involves emulating expert behavior through demonstration data to learn tasks efficiently. In contrast to trial-and-error RL, learning from demonstration resembles supervised learning, employing samples to expedite learning, minimize exploration errors, and enhance agent safety [58]. Guided by demonstrations, agents avoid stagnation and achieve faster convergence. Furthermore, demonstration learning imparts robots with insights into human intentions and behaviors, amplifying their interaction capabilities with humans [232]–[234].

Demonstration learning involves two primary methods: behavior cloning (BC) and inverse reinforcement learning (IRL) [235]–[237]. BC derives policies directly from provided datasets, suited for deterministic tasks. Techniques like the Gaussian mixture model (GMM), hidden Markov model (HMM) [238], [239], and dynamic movement primitive (DMP) [240] are widely used for trajectory modeling. However, BC is constrained to replicating simple tasks and faces difficulties with untrained tasks [181], [241], [242]. IRL learns reward functions from expert demonstrations and employs RL to find optimal policies. The reward function derived through inverse reinforcement learning exhibits greater adaptability to different task environments compared to the policy itself. It encompasses linear programming IRL [243]–[245], apprentice learning based on maximum marginal formalization [182], [246]–[248], maximum entropy IRL [249]–[255] and relative entropy IRL [256] based on probabilistic model formalization, and generative adversarial imitation learning (GAIL) inspired by generative adversarial networks (GANs) [257], [258]. GAIL directly learns policies from expert trajectories without explicit reward functions [259]–[261]. While IRL have been explored, substantial task or robot model changes may necessitate relearning, presenting implementation challenges.

Simpler demonstration learning falls short for complex tasks, as it requires an extensive dataset covering the entire task's state space. This often leads to limited agent adaptability, especially for new tasks not present in the training data. Additionally, creating a flawless demonstration dataset is costly. To tackle these issues, a combination of demonstration learning and reinforcement learning has been proposed to enhance agent adaptation and generalization [262], [263]. However, further research is needed to improve policy extension and generalization for intricate tasks. While current research has targeted specific aspects of humanoid robots, comprehensive exploration of the cooperative behaviors of complete humanoid robots is crucial [264], [265]. It is noteworthy that while simulation advancements are evident, ensuring secure transition from simulation to the real world remains a challenge.

In conclusion, demonstration learning is pivotal in humanoid robotics for swift skill acquisition, safer operation, and enhanced human interaction. Behavior cloning and inverse reinforcement learning are prevalent approaches. While behavior cloning suits deterministic tasks, it struggles with intricate or new tasks. Inverse reinforcement learning overcomes these limitations by learning rewards and optimizing policies. Challenges persist in policy generalization, dataset reliance, and simulation-to-real-world transition. Future research should target these challenges, boost agent adaptability, and explore complete humanoid robot cooperation.

V. Perception & Interaction

The perception and interaction capabilities of humanoid robots are explored in this section. It discusses the sensory systems, perception algorithms, and interaction modalities utilized by humanoid robots to understand and engage with environments.

A Sensors and Perception of Humanoid Robots

Sensors play a crucial role in enabling robots to perceive and interact with the external world. Effective fusion and utilization of sensor information serve as the foundation for sensor-based control and are prerequisites for humanoid robots to possess human-like sensing capabilities [266]–[269]. The development of high-performance sensors is essential for enabling humanoid robots to understand and adapt to complex environments while operating with precision and flexibility.

1) Visual Perception: Robot vision research is a distinct discipline due to its significance and complexity. Visual perception information processing serves as a primary technical means for robots to perceive the external world and forms the basis for constructing interactive systems within the human-robot environment. Vision algorithms are essential for extracting relevant information in real-time from acquired images [216], [254], [270], [271]. The two commonly used vision systems in humanoid robots are monocular and stereo vision systems. While monocular vision systems do not provide precise environmental information [272], stereo vision systems allow the robot to measure the distance to a target, enabling tasks such as detection and obstacle avoidance [273]–[276]. Robot vision still presents various unresolved challenges, including walking vision guidance [144], teleconferencing [277], and stereo vision [278].

2) Inertial Measurement Units (IMUs): Another essential sensor for humanoid robots, based on their bipedal nature, is the IMU. An IMU combines accelerometers, gyroscopes, and magnetometers to measure and report body-specific forces, angular velocities, and surrounding magnetic fields [279], [280]. In humanoid robots, the IMU is typically attached to the upper body and measures angles and angular velocities relative to the ground in the sagittal and frontal planes. The data generated by the IMU is initially aligned using filtering algorithms and then utilized in the development of a walking engine [131].

3) Multi-Sensor Fusion Perception: While programming can be sufficient for humanoid robots working in known environments with specific accuracy requirements, equipping them with a variety of sensors becomes crucial when operating in unstructured and complex environments [211], [281]. Humanoid robots utilize a range of sensors to support tasks such as path planning, mapping, and localization in uncertain and dynamic environments. Commonly used sensors include ultrasound [282], infrared [283], laser scanners [284], [285], camera-based vision [273], tactile sensors [286], [287], pressure sensors [288], and IMUs [279], [280]. By fusing visual feedback signals with sensor signals such as position, force/torque, and haptics, precise control of the robot in unstructured and complex environments can be achieved [289], [290].

In conclusion, sensors serve as vital tools for robots to acquire information from the environment. Vision systems, including monocular and stereo vision, play a significant role in perceiving the external world. IMUs provide crucial data for understanding the robot's orientation and motion. Moreover, the fusion of multiple sensor modalities allows humanoid robots to navigate and interact effectively in complex and unstructured environments, providing precise control and enabling tasks such as grasping and impedance control. Ongoing research in sensor development and fusion techniques is essential to further enhance the sensing capabilities of humanoid robots.

B Human-Robot-Environment Interaction

Operating alongside humans, humanoid robots necessitate versatile interaction systems for effective engagement with their environment. Within the "human-robot-environment" framework, their capacity to perceive, comprehend, and respond to surroundings is pivotal [41], [61], [153]. To establish natural interactions, they emulate human attributes through physical, cognitive, and perceptual means. Equipped with sensors and perception systems, robots gather and process data for appropriate responses. Advanced sensing technologies like vision systems and multi-sensor fusion ensure accurate environmental data [291], [292]. Beyond physical interactions, humanoid robots communicate through gestures, expressions, voice, and mobile controls. Communication technologies, including mobile and wearable devices, provide adaptable control [11], [140], [293]. This interaction framework underscores integration with the environment, striving for seamless interactions in diverse scenarios. It emphasizes adaptability, learning, and ongoing knowledge acquisition, enhancing versatility for effective navigation and responses in dynamic and unstructured surroundings [294].

In essence, the “human-robot-environment” system underscores the vital interaction and integration between humanoid robots, humans, and their surroundings. This encompasses physical, cognitive, and perceptual interactions, as well as adaptability and learning from the environment. Humanoid robots strive to be natural companions in areas such as service, healthcare, and social interaction by cultivating fluid and harmonious interactions.

VI. Potential Applications

This section introduces potential applications of humanoid robots, illustrating their versatility and potential growth. Fig. 6 provides an overview of the diverse fields where humanoid robots hold significant promise.

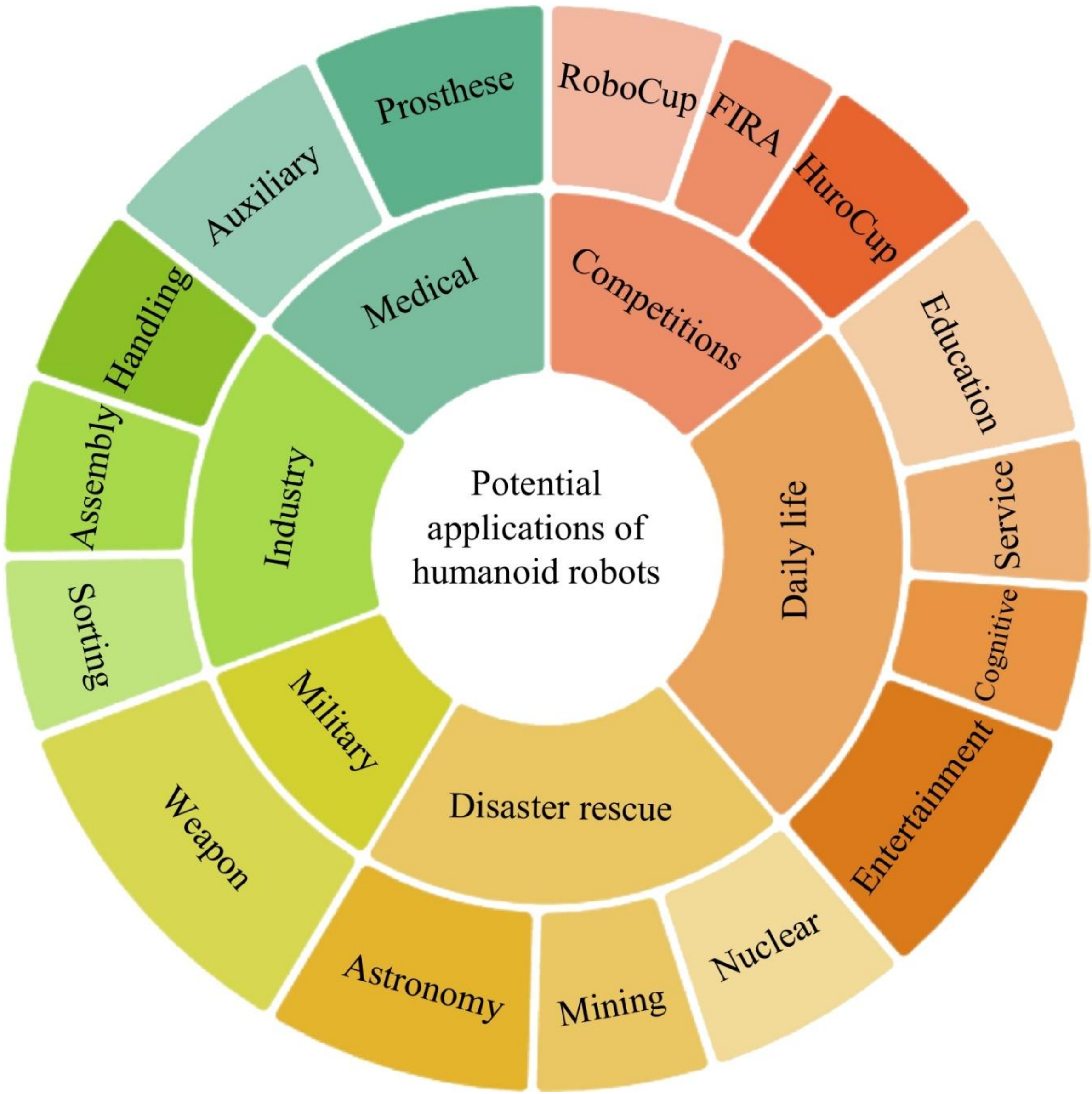


Figure 6. Potential applications of humanoid robots.

DownLoad: Full-Size Img PowerPoint

A Competitions

Competitions evaluate humanoid robots through specific tasks based on defined criteria, providing comprehensive assessments of robotic abilities. The FIRA competition concentrates on essential aspects like robot stability, intricate motion planning, and human-robot interaction, highlighting the adaptability and resilience of robot hardware and software [295]. The HuroCup league strives to craft versatile humanoid robots adept at various tasks within intricate settings, often likened to the "Olympics of robotics" [82], [296]. In contrast, the RoboCup competition, categorized by humanoid body structures, presents robotics enthusiasts with soccer tournaments that pose unique challenges [297]. The DARPA robotics challenge centers on robots executing tasks for disaster relief [298]–[300]. In summary, competitions serve as a mechanism to facilitate the enhancement of technological prowess in humanoid robots across various real-world scenarios, ultimately propelling advancement and implementation.

B Daily Life

Humanoid robots possess immense potential in the realm of living services, assuming a friendly role and fulfilling various tasks [29], [158], [301]–[303]. This application of humanoid robots has the capability to establish a new industry and market, effectively addressing the challenges posed by an aging society and mitigating the scarcity of young labor in the realms of home services and healthcare [153], [304]–[306]. Leveraging their human-like appearance, humanoid robots offer captivating and distinctive experiences within the entertainment and hospitality industry [57], [307], [308]. They can serve as entertainers, performers, or guides in venues like theme parks, museums, and exhibitions, enhancing visitor experiences and automating routine tasks in the hospitality sector [309], [310]. Moreover, humanoid robots play a transformative role in education, revolutionizing the learning process as interactive and adaptive teaching assistants. They engage students in interactive learning activities, facilitate personalized learning experiences, and provide tutoring support [311], [312]. Additionally, humanoid robots find valuable applications in research settings, enabling the exploration of human behavior, cognition, and social interaction, thereby contributing to advancements in fields such as psychology, neuroscience, and social sciences [313].

C Search and Rescue

The perilous and complex environments encountered during disaster situations present challenges for human involvement, highlighting the need for highly adaptable humanoid robots capable of substituting humans in rescue operations. Equipped with advanced mobility and sensing capabilities, humanoid robots can be deployed in search and rescue missions. They excel in accessing hazardous or inaccessible areas, navigating through debris, and locating and assisting survivors during natural disasters or emergencies. The humanoid form grants them the ability to manipulate objects and perform tasks in environments that prove arduous for traditional robots. Moreover, humanoid robots offer a stable and safe alternative to humans in operational tasks carried out in hazardous environments such as nuclear management, mining, and astronomical navigation [299].

D Military and Exploration Missions

Humanoid robots hold tremendous potential in the realm of military applications, challenging the prevailing paradigm of warfare. They can replace humans in environments marked by radiation, dust, and toxicity, performing perilous tasks or offering assistance in search operations. Additionally, humanoid robots have the capacity to support exploration missions in space and extreme environments. Their adaptability, mobility, and human-like manipulation abilities render them well-suited for aiding astronauts, conducting scientific experiments, and carrying out maintenance tasks in space stations or during planetary exploration missions [299].

E Industrial and Manufacturing

Humanoid robots can be employed in industries for repetitive and labor-intensive tasks, improving productivity and efficiency. They can collaborate with humans, providing assistance in activities such as assembly, packaging, and material handling. Equipped with advanced sensors and dexterous manipulators, humanoid robots can also contribute to complex manufacturing operations, including precision assembly and quality control [82], [296].

F Healthcare and Assistance

In the healthcare sector, humanoid robots assume a crucial role by providing valuable assistance to both patients and healthcare professionals. They can contribute to the medical rehabilitation of individuals with reduced mobility, playing a significant part in patient care [314], [315]. Humanoid robots offer support to individuals with disabilities or the elderly in various activities of daily living, including medication reminders, mobility assistance, and personal care. Furthermore, they can assist healthcare providers in tasks such as patient monitoring, data collection, and telemedicine, leading to reduced workloads and improved healthcare delivery. Moreover, humanoid robots hold the potential to function as prostheses, aiding paralyzed patients in realizing their aspiration to walk [60], [194], [301].

The extensive array of potential applications outlined for humanoid robots underscores their versatility and capacity to contribute significantly across diverse fields. Continued research and development in humanoid robotics will further unlock their potential and pave the way for their integration into various industries, shaping the future of human-robot collaboration and interaction.

VII. Future Development Trends and Challenges

This section discusses the future trends and challenges, offering insights into research and development directions and identifying key obstacles for advancing the field.

A New Challenges

In recent years, humanoid robotics has experienced significant growth, driven by increased interest, investments, and research advancements. Notable events, like Honda discontinuing ASIMO and Boston Dynamics changing ownership, underscore the dynamic nature of the field. While bipedal robots have made progress, their future is marked by uncertainty and complexity, with technical, financial, market, and societal challenges [316], [317]. Summarizing these limiting factors is vital for guiding research, resource allocation, and decision-making [318].

1) Biological Mechanism: The understanding of the biological mechanism behind humanoidism remains limited, resulting in a lack of comprehensive knowledge and simplistic models. The complexity of the biological mechanism has yet to be fully revealed and understood.

2) Biological Structure: The mechanical structure of humanoid robots is designed and driven in a conventional manner, lacking the rationality and intricacy of the human body structure. There is a need to develop mechanical structures that more accurately replicate the sophistication and functionality of the human body.

3) Biological Material: The research on new biological materials with high performance is insufficient, and the existing findings have not been effectively applied and widely disseminated. Further exploration and utilization of advanced biological materials are necessary to enhance the capabilities and performance of humanoid robots.

4) Biological Control: The control and learning methods employed in humanoid robotics often rely on traditional approaches, with limited breakthroughs in the utilization of biological control methods such as neural control and myoelectric control. A deeper understanding of brain-like intelligence mechanisms and biological neuroscience is crucial to unlocking the full potential of humanoid robots.

5) Biological Energy: The research on biological energy conversion mechanisms in humanoid robots is not sufficiently profound, resulting in low energy utilization rates and high energy consumption. Further investigations into the efficient conversion and utilization of biological energy sources are essential to enhance the energy efficiency of humanoid robots.

6) Technological Complexity: Developing humanoid robots with natural movements demands advanced control and sensing technologies. Addressing challenges like stable bipedal motion and human-like interaction require progress in sensor tech, AI, and mechatronics, along with interdisciplinary collaboration.

7) Energy Efficiency: Bipedal robots' high energy demands call for more efficient power systems and energy management. Advancements in battery tech hold potential to extend robot runtime, enabling broader applications.

8) Costs: High development and maintenance costs limit commercial adoption. Future research should optimize manufacturing, materials, and production for cost reduction and wider usage.

9) Application Domains: Despite potential applications in areas like emergency response and healthcare, robot performance, safety, and costs must align with specific needs. Collaborative research and industry partnerships are vital for broader adoption.

10) Machine Learning and AI: Advancing machine learning and AI is crucial for enhancing robot autonomy and adaptability.

11) Legal and Ethical Issues: As robots integrate into society, ethical and legal concerns arise. Future research should focus on regulations and ethics to ensure lawful and ethical robot use, necessitating interdisciplinary work and responsible advancement.

12) User Acceptance: Future developments should enhance robot appearance, movements, and communication to improve user acceptance and interaction.

13) Fault Tolerance and Safety: Ensuring robot stability and safety is critical. Collaborative efforts in technology and regulation are essential for reliable, safe robot deployment in various applications.

Table V provides a comprehensive overview of key technologies and challenges for the future progress of humanoid robots. Tackling these challenges necessitates interdisciplinary collaboration and advancements in areas like biology, materials science, control systems, and energy conversion.

Table V. Key Technologies and Challenges of Humanoid Robots

Key technology	Challenge
Biological mechanism	√√ **Accurate modelling of biological movement mechanisms**
	√√ **Prototypes of humanoid robots are far from what humans can actually do**
	The human body is a very complex system and each of its motor functions is acted upon by multiple factors such as the skeletal, muscular and nervous systems.
	The existing experimental conditions and research methods for the study of biological mechanisms do not fully meet the requirements for the observation of the corresponding biological movement patterns.
	The study of biological mechanisms requires close and long-term multidisciplinary cooperation.
Biological structure	√√ **Movement mechanism**
	Rigid and flexible organizational structure
	Strong motion performance and environmental adaptability
	The human body has the characteristics of flexibility, high energy efficiency and lightweightness.

Key technology	Challenge
	√√ **Driving** Biological drive systems can generate enormous amounts of energy by consuming only minute amounts of chemical substances, combined with the appropriate bio-conversion methods.
Biological material	√√ **Biomimetic materials have the most rational macro and micro structures** Biomimetic materials are self-adaptive and self-healing and are optimal in terms of overall properties such as specific strength, specific stiffness and toughness. The use of biomimetic materials allows for excellent properties such as bio-damping, wear resistance, fatigue resistance, anti-adhesion and self-cleaning.
Biological control	√√ **Biological control system** Biological control aims to achieve accurate positioning and flexible motion control by truly simulating biology. √√ **Excellent environmental awareness** √√ **Human-like decision-making capacity**
Biological energy	√√ **Most humanoid robots suffer from low energy utilisation and high energy consumption** The conversion of biological energy involves the microstructure of organisms and the related chemistry and physics of many disciplines. The high energy demands of robots call for more efficient power systems and energy management.
Complexity, cost and application	√√ **Interdisciplinary collaboration** √√ **High development and maintenance costs** √√ **Specific needs according to the application of humanoid robots**
Acceptance and security	√√ **The development of humanoid robots need to improve user acceptance and interaction**

Key technology	Challenge
	Legal and ethical constraints can make humanoid robots more acceptable to the public.
	The fault tolerance and safety of the robot are critical factors for user acceptance.

| Show Table

DownLoad: CSV

B Future Development Trends

Humanoid robotics research hinges on understanding biology and interdisciplinary collaboration. Challenges are surmountable through technology, cost-efficiency, and regulations. Innovations in materials, batteries, and AI will strengthen bipedal robots, enhancing energy efficiency and adaptability, with their future dependent on breakthroughs, cost-effectiveness, and broader applications, yielding significant societal benefits.

1) Biological Mechanism: The profound study of human anatomy, physiology, and coordination provides invaluable insights into the fundamental principles governing human capabilities [319]. This knowledge serves as the foundation for developing humanoid robots with enhanced functionality and lifelike characteristics. The field of biomimetic mechanisms has evolved from the macro level to the micro level, with ongoing biological research unraveling the intricate mechanisms that govern humanoid robots [320]. Despite significant progress, the current intelligence exhibited by humanoid robots falls short of human capabilities [321]. Hence, future research focuses on advancing brain-like intelligence technologies that emulate the human nervous system, aimed at replicating human-like cognitive behavior and intelligence through neural and cognitive-behavioral mechanisms. The ultimate goal is to equip humanoid robots with a range of human-like cognitive abilities, surpassing current intelligence levels [48], [49], [322]. This pursuit integrates insights from biology, neuroscience, and robotics, unlocking the potential for advanced cognitive capabilities in humanoid robots, bringing them closer to the realm of human intelligence [14], [318], [323].

2) Biological Sensing and Perception: The future of humanoid robotics is set to undergo a profound transformation with the emergence of highly accurate and affordable sensors. These sensors will play a pivotal role in enabling advanced functionalities and capabilities within humanoid robots. By providing precise and reliable data from both the robot's surroundings and its internal systems, these sensors will enhance perception, interaction, and decision-making processes. Their impact will extend across various domains, including human-robot collaboration, autonomous navigation, and intelligent manipulation tasks [216]. Furthermore, the affordability of these sensors will foster widespread adoption, making humanoid robots more accessible and applicable in real-world scenarios. In summary, the development of accurate and cost-effective sensors holds immense promise in unlocking the full potential of humanoid robotics and shaping its future trajectory [268], [269]. Intelligent sensing and perception form the cornerstone of human-robot, robot-robot, and robot-environment interactions, with key research directions encompassing multi-sensor information fusion, object perception, and recognition technologies [320]. By harnessing the collective information from vision, hearing, touch, and other sensor modalities, robots can surpass human perceptual capabilities and adapt to complex and unstructured environments [211], [267], [288]. Leveraging the strengths of multiple sensors through rationalized utilization, robots achieve a coherent interpretation and description of the observed environment. Object perception and recognition technologies offer efficient computation and accurate identification. The future of humanoid robot cognition and perception relies on advancements in sensor technology, artificial intelligence, and computational performance, driving the intelligent evolution of humanoid robots [324]–[326].

3) Biological Structure: Bionic structures in humanoid robots have evolved from rigid to integrated designs that combine rigidity and flexibility. This integration allows for more natural movements resembling humans, enhancing versatility and adaptability. By incorporating flexible elements, humanoid robots achieve a balance between stability and agility, enabling them to perform complex tasks efficiently. This progression signifies a significant advancement in humanoid robotics, as robots can now better emulate human behaviors and exhibit enhanced capabilities.

a) Architecture design: The architecture design of a humanoid robot is crucial as it defines the relationships and distribution of its components. It determines how information flows and how the robot's processing and control system is structured. Achieving robot autonomy relies on careful architecture design, which is essential for reaching this goal. Addressing architectural aspects and providing guidance is highly valuable in theory and practice [69], [155], [157], [158].

b) Mechanical structural design: The mechanical design of a humanoid robot is important for its acceptance and human-like appearance [153]–[155]. Achieving intelligence, versatility, adaptability, and flexibility of movement is crucial. Humanoid robots are complex systems with multiple joints and degrees of freedom. The challenge is to optimize the structure while ensuring the desired functionality [69], [156], [308].

c) Advanced actuators: Traditional motor-driven methods are commonly used in humanoid robots, but they have limitations like restricted movement, limited load capacity, and heat generation. New hydraulic actuators have been explored to increase load capacity, but their high cost limits their widespread use. Artificial muscles that simulate human muscle-driven joint movements through airbag inflation and deflation are also being developed, but they have drawbacks like slow movement and low control accuracy. Advancing actuator technologies is crucial to improve load capacity and motion performance in humanoid robots [209].

4) Biological Materials: The future of humanoid robots involves the incorporation of biological materials, which will revolutionize their design and functionality. These materials imitate the structure and properties of biological systems, enabling robots to replicate human movements with enhanced precision and dexterity. The development of biomimetic materials has progressed from traditional approaches to encompass integrated structures, driving mechanisms, and material integration [269], [327], [328]. By leveraging the principles and interactions observed in biological systems, these materials provide technical support for robots to achieve human-like behavioral functions while optimizing energy consumption, efficiency, and adaptability to the environment [325], [326], [329]. The advancement of materials and the improvement of precision in manufacturing and component assembly are crucial considerations in the development process [154], [268]. In-depth research and application of biomimetic materials and structures will pave the way for advancements in bio-mechanical-electrical integration technology, bionic control theory, and bionic drive systems, among other related fields [320], [330], [331].

5) Biological Control: The future of humanoid robot control is promising, driven by advances in control systems and AI. Collaboration between robotics engineers and control experts will be key to developing advanced algorithms that mimic human-like control mechanisms, enhancing robot capabilities. However, achieving the finesse and adaptability of human motion remains a formidable challenge. Currently, humanoid robots lack full autonomy and depend on preprogrammed instructions and external input [14]. Achieving full autonomy requires significant advancements in AI and robotics. Future trends in humanoid robot control include a focus on key areas:

a) Optimization-based control: In the realm of optimization-based locomotion control for humanoid robots, future trends include improving real-time adaptability, refining motion quality, and prioritizing multi-objective optimization. Adaptive terrain recognition, enhanced human-robot collaboration, and the integration of deep learning techniques will further shape this field. Interdisciplinary collaboration and real-world testing are expected to push the boundaries of adaptability and versatility in humanoid robotics [294], [332], [333].

b) Thinking and decision making: The evolution of biomimetic control is moving towards brain-like intelligence and fine-grained neuron-level control [14]. Future trends in thinking and decision-making for humanoid robots involve advancements in cognitive computing, AI, natural language processing, and machine learning. These robots will become more autonomous and adept at interacting with humans. They'll leverage big data and adhere to ethical considerations [220], [334].

c) Continuous learning: The future of learning control for humanoid robots holds promising developments. Deep reinforcement learning and the fusion of learning with optimization methods will enhance adaptability and performance in real-world scenarios [58], [214]. Autonomous learning, advanced perception, and standardized evaluation metrics will drive progress. Humanoid robots will become more autonomous, versatile, and capable in various domains [322], [335]. Future developments emphasize continuous learning, enabling robots to adapt and acquire new skills as they encounter different environments.

d) Remote control: Future trends in remote control for humanoid robots include improved teleoperation interfaces, reduced latency through advanced communication technologies, augmented reality integration, autonomous features, and standardization. These advancements will enhance the versatility and usability of humanoid robots in various applications [30].

e) Dynamic multi-objective optimization: Dynamic multi-objective optimization techniques are being explored to improve performance in various aspects [336]. Achieving a balance between stability, speed, cost, safety, efficiency, and adaptability in dynamic, complex environments remains a challenge [337]. Developing robust, real-time optimization algorithms will be essential for quick adaptation to environmental changes [338].

f) Autonomy: Advancements in autonomy will reduce the reliance on teleoperation, empowering robots to make independent decisions in unstructured environments.

g) Safety and ethics: Ensuring the safety and ethical use of humanoid robots, particularly in sensitive domains like healthcare and caregiving, remains a significant challenge. Control algorithms will need to incorporate safety measures to prevent accidents.

h) Human-like dexterity: Achieving human-level dexterity in robot hands is an ongoing challenge. Research will focus on improving control algorithms for fine-grained manipulation and complex tasks.

i) Energy efficiency: Enhancing energy efficiency is crucial for practical applications of humanoid robots. Future control algorithms will need to optimize energy consumption to extend operational durations.

j) Interdisciplinary collaboration: Collaboration with fields such as neuroscience and biomechanics will continue to inform humanoid robot control research, leading to more human-like control strategies.

k) Regulation and standardization: As humanoid robots become more prevalent, there will be a growing need for regulation and standardization in control systems to ensure safety and interoperability across different platforms.

The convergence of these challenges and trends will shape the next phase of developments in humanoid robot control, enabling robots to perform increasingly sophisticated tasks and interact more naturally with humans across diverse contexts.

6) Biological Energy: Advancements in energy conversion technologies are crucial towards addressing the high energy consumption and low energy utilization rate in humanoid robots [339]. Research should focus on efficient mechanisms for converting and utilizing biological energy sources to power these robots. By studying biological energy conversion mechanisms and developing innovative solutions for energy storage and management, humanoid robot systems can become more energy-efficient. Currently, portable rechargeable battery packs, such as Li-PO batteries, are commonly used to power humanoid robots due to their high energy density, small size, and fast recharge cycles [340]–[342]. In some cases, portable generators are also utilized [42]. Optimizing energy consumption in humanoid robots is an active area of research, with efforts focused on parameter optimization and improving drive sources to make them smaller, lighter, and higher in capacity. The ideal energy source for humanoid robots should possess high energy density, high temperature resistance, corrosion resistance, renewability, and low cost. However, the current capacity of self-contained energy sources is limited, and the development of humanoid robots with multiple joints presents the challenge of improving the drive source. Solving these challenges will contribute to the advancement of humanoid robot development [343]–[346].

7) Software System: In recent years, there has been a focus on reducing software development efforts in humanoid robots through the introduction of robot operating system (ROS) packages specifically designed for humanoid robots and their actuators [279], [280]. ROS is supported by useful simulators like the open-source Gazebo [347], [348]. However, some developers may opt for alternative platforms for humanoid robot development [349]–[351]. The software systems for humanoid robots encompass a wide range of programming languages and platforms. To streamline the development process, there is a pressing need for a comprehensive software development system and platform that includes a complete development library and cloud service toolbox for humanoid robotic systems. This would promote uniformity and accelerate the implementation process. Furthermore, the establishment of a cloud-based robotics system enables global information and knowledge sharing, resource sharing among humanoid robots, and efficient computation and data storage through cloud computing and storage functions. However, this emerging technology still requires further research and exploration to address issues such as resource allocation, system security, and reliable communication protocols [15].

8) Multi-Humanoid Robots System: Multi-robot systems have received significant research attention for facilitating collaboration and coordination among robots in shared environments [352]. However, the complexities associated with humanoid robots and the nascent stage of their technologies have hindered in-depth investigation into multi-humanoid robot systems [353]–[356]. This research gap calls for future exploration focused on task allocation, group decision making, and resource sharing within such systems, with the aim of realizing comprehensive and practical implementations [336].

9) Human-Robot Coexistence Safety: Safe human-robot coexistence in humanoid robots is crucial, requiring a focus on flexible mechanism design, control strategies, and safety methods [158], [292], [308], [357]. Research includes active flexibility with multi-sensor fusion and adaptable control, and passive flexibility through mechanism design and bionic materials [27], [304], [358]. The future of humanoid robotics is aimed towards natural human-robot interaction with advanced sensors, algorithms, and interfaces. Public perceptions and acceptance must be considered to shape their responsible deployment. These advancements will enable seamless integration of humanoid robots into human-centric environments while prioritizing safety.

10) Human-Robot Interaction System: The human-robot interaction system plays a vital role in enabling expressive communication and cognitive capabilities in humanoid robots [17], [359], [360]. Current research focuses on enhancing multimodal information fusion techniques to broaden the interactive capabilities of robots, with particular emphasis on semantic analysis of speech [294], [310]. Humanoid robots are actively developing interactive performance to address labor shortages and are progressing towards more flexible working models [140], [291], [361]. As human-computer interaction technology advances, humanoid robots are becoming adaptable for a wide range of scenarios. Future research directions include the integration of advanced language models, such as OpenAI's ChatGPT, and the exploration of large-scale robot operations, offering exciting prospects for enhancing human-robot interactions [11], [15].

11) Interdisciplinary Research: The pursuit of humanoidism requires interdisciplinary research. Biologists study human anatomy and physiology, while materials scientists develop advanced materials for durable robot structures [362]–[365]. Collaboration between robotics, AI, neuroscience, and other fields is crucial for bipedal robot advancement [366]. Interdisciplinary collaboration can drive innovation in control algorithms, sensors, and cognition, enhancing robot performance [367]. This approach aims to create more functional humanoid robots with accurate human emulation, benefiting various domains.

12) The Crucial Role of Academia: Academia plays a vital role in advancing humanoid robotics by focusing on foundational research, ethical considerations, and talent development [368]–[370]. In research, academic institutions explore theoretical foundations, algorithms, and cognitive challenges, providing the theoretical basis for practical applications. Additionally, academia leads discussions on ethical frameworks and societal impacts, guiding ethical development. In talent development, academic institutions nurture experts through comprehensive education and interdisciplinary training. Academia's organizational characteristics further support the field. Interdisciplinary collaboration fosters innovation, while long-term vision expands the field's boundaries. Knowledge dissemination strengthens scholarly aspect through publications and presentations. Collaborating with the industry, academia enhances humanoid robotics by promoting initiatives like joint projects, internships, and technology transfer. Supporting startups, open-source platforms, and dedicated liaison offices accelerate research and development. Academia's expertise in ethics informs responsible industry practices and regulations.

Therefore, the key technologies of the humanoid robot are summarized in Fig. 7. In conclusion, the future of humanoid robotics lies in embracing multidisciplinary collaboration and pushing the boundaries of biological understanding. By integrating structure and biological materials, humanoid robots will exhibit enhanced functionality, expand their applications, and transform various aspects of human life. As research and technology progress, the potential for humanoid robots to become integral components of society grows, opening up exciting possibilities for their integration into everyday life.

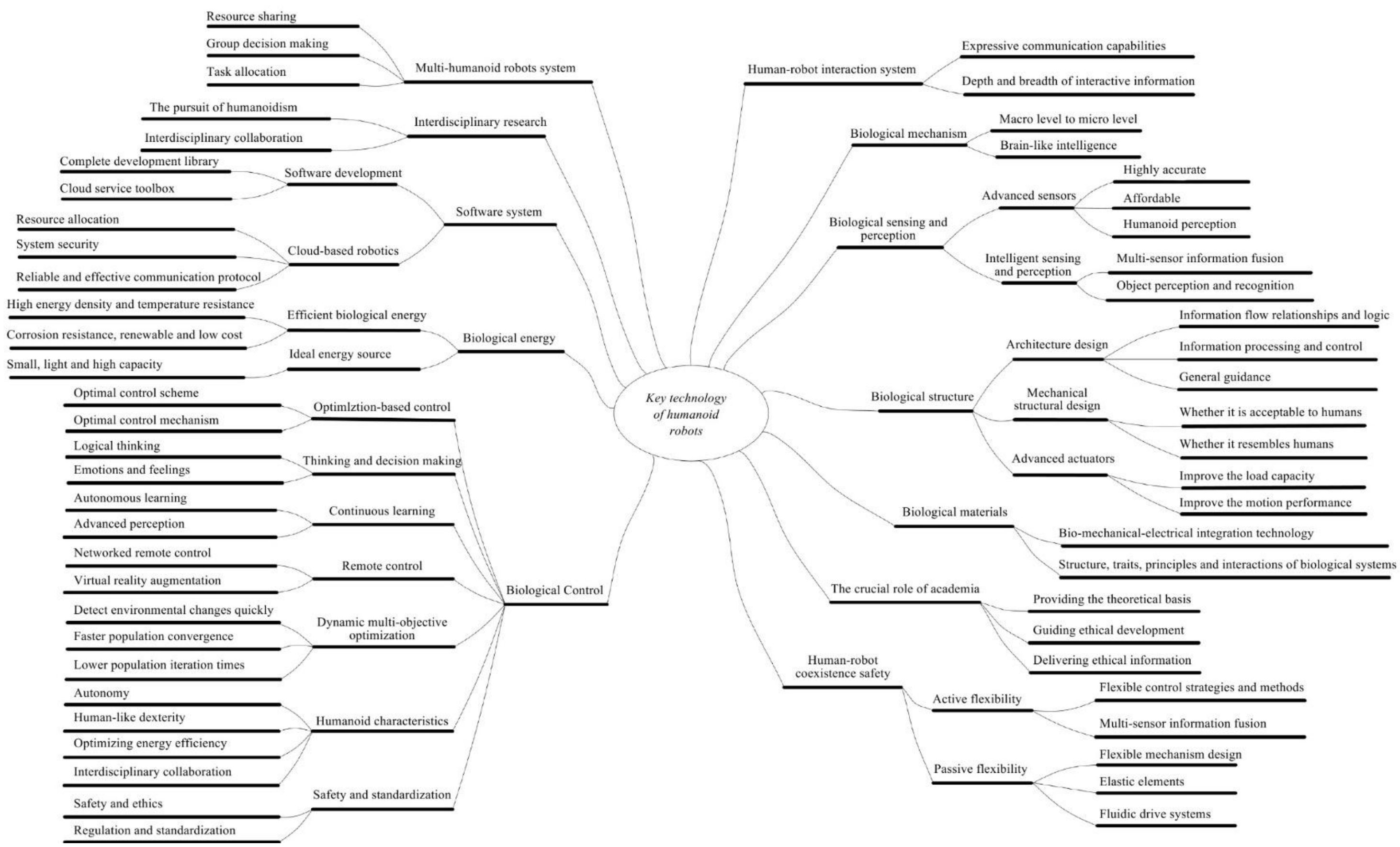


Figure 7. Key technologies of humanoid robots.

DownLoad: Full-Size Img PowerPoint

VIII. Conclusion and Future Work

This comprehensive review provides a thorough examination of the advancements and future prospects in humanoid robots. By investigating various research endeavors and key technologies, such as ontology structure, control and decision-making, perception and interaction, a comprehensive overview of the current research state is presented. The review identifies emerging challenges, including the need for a deeper understanding of biological motion mechanisms, improved structural design, enhanced material applications, advanced drive and control methods, and efficient energy utilization. Emphasizing the integration of bionics, brain-inspired intelligence, mechanics, and control, this review highlights a promising direction for the development of advanced humanoid robotic systems. The insights and guidance offered in this paper make it a valuable resource for researchers in the field of humanoid robotics, contributing to the advancement of humanoid robots that exhibit capabilities closer to those of humans.

- ## References

[1] G.-Z. Yang, "Robot learning-Beyond imitation," *Sci. Robot.*, vol. 4, no. 26, p. eaaw3520, Jan. 2019. doi: 10.1126/scirobotics.aaw3520

[2] R. Baines, S. K. Patiballa, J. Booth, L. Ramirez, T. Sipple, A. Garcia, F. Fish, and R. Kramer-Bottiglio, "Multi-environment robotic transitions through adaptive morphogenesis," *Nature*, vol. 6 no. 7931, pp. 283–289, Oct. 2022. doi: 10.1038/s41586-022-05188-w

[3] A. Vishwanath, A. Singh, Y. H. V. Chua, J. Dauwels, and N. Magnenat-Thalmann, "Humanoid co-workers: How is it like to work with a robot?" in *Proc. 28th IEEE Int. Conf. Robot and Human Interactive Communication*, New Delhi, India, 2019, pp. 1–6.

[4] J. Cui and J. Trinkle, "Toward next-generation learned robot manipulation," *Sci. Robot.*, vol. 6, no. 54, p. eabd9461, May 2021. doi: 10.1126/scirobotics.abd9461

[5] F. Yuan, M. Boltz, D. Bilal, Y.-L. Jao, M. Crane, J. Duzan, A. Bahour, and X. Zhao, "Cognitive exercise for persons with Alzheimer's disease and related dementia using a social robot," *IEEE Trans. Robot.*, vol. 39, no. 4, pp. 3332–3346, 2023. doi: 10.1109/TRO.2023.3272846

[6] I. Chavdarov, K. Yovchev, L. Miteva, A. Stefanov, and D. Nedanovski, "A strategy for controlling motions related to sensory information in a walking robot big foot," *Sensors*, vol. 23, no. 3, p. 150 Jan. 2023. doi: 10.3390/s23031506

[7] F. Gama, M. Shcherban, M. Rolf, and M. Hoffmann, "Goal-directed tactile exploration for body model learning through self-touch on a humanoid robot," *IEEE Trans. Cogn. Dev. Syst.*, vol. 15, no 2, pp. 419–433, Jun. 2023. doi: 10.1109/TCDS.2021.3104881

[8] T. Hara, T. Sato, T. Ogata, and H. Awano, "Uncertainty-aware haptic shared control with humano robots for flexible object manipulation," *IEEE Robot. Autom. Lett.*, vol. 8, no. 10, pp. 6435–6442, Oct. 2023. doi: 10.1109/LRA.2023.3306668

[9] S. Saeedvand, M. Jafari, H. S. Aghdasi, and J. Baltes, "A comprehensive survey on humanoid robo development," *Knowl. Eng. Rev.*, vol. 34, p. e20, Dec. 2019. doi: 10.1017/S0269888919000158

[10] F. Rubio, F. Valero, and C. Llopis-Albert, "A review of mobile robots: Concepts, methods, theoretical framework, and applications," *Int. J. Adv. Robot. Syst.*, vol. 16, no. 2, Apr. 2019.

[11] C. Tsiourti, A. Weiss, K. Wac, and M. Vincze, "Multimodal integration of emotional signals from voice, body, and context: Effects of (in) congruence on emotion recognition and attitudes towards robots," *Int. J. Soc. Robot.*, vol. 11, no. 4, pp. 555–573, Feb. 2019. doi: 10.1007/s12369-019-0052

[12] A. Goswami and P. Vadakkepat, *Humanoid Robotics: A Reference*. Dordrecht, The Netherlands: Springer, 2019.

[13] B. Siciliano and O. Khatib, *Springer Handbook of Robotics*. 2nd ed. Cham, Germany: Springer, 20

[14] J. Merel, M. Botvinick, and G. Wayne, "Hierarchical motor control in mammals and machines," *N Commun.*, vol. 10, no. 1, p. 5489, Dec. 2019. doi: 10.1038/s41467-019-13239-6

[15] S. Sathyavenkateshwaren and S. Malathi, “Humanoid robot: A survey on communication, tracking and voice recognition,” in *Proc. 3rd Int. Conf. Inventive Computation Technologies*, Coimbatore, India, 2018, pp. 555–560.

[16] G. Taga, Y. Yamaguchi, and H. Shimizu, “Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment,” *Biol. Cybern.*, vol. 65, no. 3, pp. 147–159, Jul. 1991. doi: 10.1007/BF00198086

[17] G. Taga, “Global entrainment in the brain-body-environment: Retrospective and prospective views,” *Biol. Cybern.*, vol. 115, no. 5, pp. 431–438, Oct. 2021. doi: 10.1007/s00422-021-00898-2

[18] T. Reil and P. Husbands, “Evolution of central pattern generators for bipedal walking in a real-time physics environment,” *IEEE Trans. Evol. Computat.*, vol. 6, no. 2, pp. 159–168, Apr. 2002. doi: 10.1109/4235.996015

[19] W. Huang, C.-M. Chew, Y. Zheng, and G.-S. Hong, “Pattern generation for bipedal walking on slopes and stairs,” in *Proc. 8th IEEE-RAS Int. Conf. Humanoid Robots*, Daejeon, South Korea, 200 pp. 155–160.

[20] J. M. Wang, D. J. Fleet, and A. Hertzmann, “Optimizing walking controllers for uncertain inputs an environments,” *ACM Trans. Graph.*, vol. 29, no. 4, p. 73, Jul. 2010.

[21] J. R. Jeffers, A. G. Auyang, and A. M. Grabowski, “The correlation between metabolic and individ leg mechanical power during walking at different slopes and velocities,” *J. Biomech.*, vol. 48, no. 1 pp. 2919–2924, Aug. 2015. doi: 10.1016/j.jbiomech.2015.04.023

[22] S. Wang, W. Chaovalitwongse, and R. Babuska, “Machine learning algorithms in bipedal robot control,” *IEEE Trans. Syst. Man Cybern. Part C* (*Appl. Rev.*), vol. 42, no. 5, pp. 728–743, Sept. 2012. doi: 10.1109/TSMCC.2012.2186565

[23] A. G. Di Nuovo, D. Marocco, S. Di Nuovo, and A. Cangelosi, “Autonomous learning in humanoid robotics through mental imagery,” *Neural Netw.*, vol. 41, pp. 147–155, May 2013. doi: 10.1016/j.neunet.2012.09.019

[24] M. Jafari, S. Saeedvand, and H. S. Aghdasi, “A hybrid Q-learning algorithm to score a moving ball for humanoid robots,” in *Proc. 5th IEEE Conf. Knowledge Based Engineering and Innovation*, Tehran, Iran, 2019, pp. 498–503.

[25] T. Sugihara and M. Morisawa, “A survey: Dynamics of humanoid robots,” *Adv. Robot.*, vol. 34, no 21–22, pp. 1338–1352, Jun. 2020. doi: 10.1080/01691864.2020.1778524

[26] Y. Tazaki and M. Murooka, “A survey of motion planning techniques for humanoid robots,” *Adv. Robot.*, vol. 34, no. 21–22, pp. 1370–1379, Aug. 2020. doi: 10.1080/01691864.2020.1803128

[27] M. Destephe, A. Henning, M. Zecca, K. Hashimoto, and A. Takanishi, “Perception of emotion and emotional intensity in humanoid robots gait,” in *Proc. IEEE Int. Conf. Robotics and Biomimetics*, Shenzhen, China, 2013, pp. 1276–1281.

[28] J. J. Steil, F. Röthling, R. Haschke, and H. Ritter, “Situated robot learning for multi-modal instructi and imitation of grasping,” *Robot. Auton. Syst.*, vol. 47, no. 2-3, pp. 129–141, Jun. 2004. doi: 10.1016/j.robot.2004.03.007

[29] G. McCartney and A. McCartney, “Rise of the machines: Towards a conceptual service-robot research framework for the hospitality and tourism industry,” *Int. J. Contemp. Hospitality Manage.*, vol. 13, no. 12, pp. 3835–3851, Dec. 2020.

[30] K. Darvish, L. Penco, J. Ramos, R. Cisneros, J. Pratt, E. Yoshida, S. Ivaldi, and D. Pucci, “Teleoperation of humanoid robots: A survey,” *IEEE Trans. Robot.*, vol. 39, no. 3, pp. 1706–1727, Jun. 2023. doi: 10.1109/TRO.2023.3236952

[31] H. Hemami and B.-R. Chen, “Stability analysis and input design of a two-link planar biped,” *Int. J. Robot. Res.*, vol. 3, no. 2, pp. 93–100, Jun. 1984. doi: 10.1177/027836498400300208

[32] L. Li, Z. Xie, and X. Luo, “Impact dynamics and parametric analysis of planar biped robot,” in *Pro 25th Int. Conf. Mechatronics and Machine Vision in Practice*, Stuttgart, Germany, 2018, pp. 97–10

[33] R. Ozawa and Y. Kojima, “Control of a powered planar biped without ankle actuation,” in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Taipei, China, 2010, pp. 3617–3622.

[34] J. P. Schmiedeler, E. R. Westervelt, and A. R. Dunki-Jacobs, “Integrated design and control of a biped robot,” in *Proc. Int. Design Engineering Technical Conf. Computers and Information in Engineering Conf.*, Long Beach, USA, 2005, pp. 167–173.

[35] M. Hirose and K. Ogawa, “Honda humanoid robots development,” *Phil. Trans. Roy. Soc. A: Math. Phys. Eng. Sci.*, vol. 365, no. 1850, pp. 11–19, Jan. 2007.

[36] T. Ishida, “Development of a small biped entertainment robot QRIO,” in *Proc. Micro-NanoMechatronics and Human Science and 4th Symp. Micro-Nanomechatronics for Information-Based Society*, Nagoya, Japan, 2004, pp. 23–28.

[37] C. Azevedo, “Control architecture and algorithms of the anthropomorphic biped robot-BIP2000,” in *Proc. 3rd Int. Conf. Climbing and Walking Robots*, London, UK, 2000, pp. 285–293.

[38] M. Fujita, Y. Kuroki, T. Ishida, and T. T. Doi, “A small humanoid robot SDR-4X for entertainmen applications,” in *Proc. IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics*, Kobe, Japan, 20 pp. 938–943.

[39] J.-H. Oh, D. Hanson, W.-S. Kim, Y. Han, J.-Y. Kim, and I.-W. Park, “Design of android type humanoid robot Albert HUBO,” in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Beijing, China, 2006, pp. 1428–1433.

[40] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura, “The intellige ASIMO: System overview and integration,” in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Lausanne, Switzerland, 2002, pp. 2478–2483.

[41] A. De Santis, B. Siciliano, A. De Luca, and A. Bicchi, “An atlas of physical human-robot interaction,” *Mech. Mach. Theory*, vol. 43, no. 3, pp. 253–270, Mar. 2008. doi: 10.1016/j.mechmachtheory.2007.03.003

[42] S. Kuindersma, R. Deits, M. Fallon, A. Valenzuela, H. Dai, F. Permenter, T. Koolen, P. Marion, ar R. Tedrake, “Optimization-based locomotion planning, estimation, and control design for the Atlas humanoid robot,” *Auton. Robot.*, vol. 40, no. 3, pp. 429–455, Mar. 2016. doi: 10.1007/s10514-015-9479-3

[43] K. Khokar, P. Beeson, and R. Burridge, "Implementation of KDL inverse kinematics routine on the Atlas humanoid robot," *Proc. Comput. Sci.*, vol. 46, pp. 1441–1448, Dec. 2015. doi: 10.1016/j.procs.2015.02.063

[44] G. Nelson, A. Saunders, N. Neville, B. Swilling, J. Bondaryk, D. Billings, C. Lee, R. Playter, and M Raibert, "PETMAN: A humanoid robot for testing chemical protective clothing," *J. Robot. Soc. Japan*, vol. 30, no. 4, pp. 372–377, May 2012. doi: 10.7210/jrsj.30.372

[45] S. Sakai and Y. Maeshima, "A new method for parameter identification for N-DOF hydraulic robo in *Proc. IEEE Int. Conf. Robotics and Automation*, Hong Kong, China, 2014, pp. 5983–5989.

[46] J. Banks, "Optimus primed: Media cultivation of robot mental models and social judgments," *Fron Robot. AI*, vol. 7, p. 62, May 2020. doi: 10.3389/frobt.2020.00062

[47] X. Shu, F. Ni, X. Fan, S. Yang, C. Liu, B. Tu, Y. Liu, and H. Liu, "A versatile humanoid robot platform for dexterous manipulation and human-robot collaboration," *CAAI Trans. Intell. Technol.* 2023. DOI: 10.1049/cit2.12214

[48] H. Qiao, J. Chen, and X. Huang, "A survey of brain-inspired intelligent robots: Integration of visio decision, motion control, and musculoskeletal systems," *IEEE Trans. Cybern.*, vol. 52, no. 10, pp. 11267–11280, Oct. 2022. doi: 10.1109/TCYB.2021.3071312

[49] H. Qiao, Y.-X. Wu, S.-L. Zhong, P.-J. Yin, and J.-H. Chen, "Brain-inspired intelligent robotics: Theoretical analysis and systematic application," *Mach. Intell. Res.*, vol. 20, no. 1, pp. 1–18, Jan. 2023. doi: 10.1007/s11633-022-1390-8

[50] Q. Huang, C. Dong, Z. Yu, X. Chen, Q. Li, H. Chen, and H. Liu, "Resistant compliance control for biped robot inspired by humanlike behavior," *IEEE/ASME Trans. Mechatron.*, vol. 27, no. 5, pp. 3463–3473, Oct. 2022. doi: 10.1109/TMECH.2021.3139332

[51] G. Metta, L. Natale, F. Nori, G. Sandini, D. Vernon, L. Fadiga, C. von Hofsten, K. Rosander, M. Lopes, J. Santos-Victor, A. Bernardino, and L. Montesano, "The *iCub* humanoid robot: An open-systems platform for research in cognitive development," *Neural Netw.*, vol. 23, no. 8–9, pp. 1125–1134, Oct.–Nov. 2010. doi: 10.1016/j.neunet.2010.08.010

[52] N. G. Tsagarakis, G. Metta, G. Sandini, D. Vernon, R. Beira, F. Becchi, L. Righetti, J. Santos-Victo A. J. Ijspeert, M. C. Carrozza, and D. G. Caldwell, "iCub: The design and realization of an open humanoid platform for cognitive and neuroscience research," *Adv. Robot.*, vol. 21, no. 10, pp. 1151 1175, Oct. 2007. doi: 10.1163/156855307781389419

[53] C. Fu and K. Chen, "Gait synthesis and sensory control of stair climbing for a humanoid robot," *IE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 2111–2120, May 2008. doi: 10.1109/TIE.2008.921205

[54] S. Caron, A. Escande, L. Lanari, and B. Mallein, "Capturability-based pattern generation for walki with variable height," *IEEE Trans. Robot.*, vol. 36, no. 2, pp. 517–536, Apr. 2020. doi: 10.1109/TRO.2019.2923971

[55] T. Koolen, T. de Boer, J. Rebula, A. Goswami, and J. Pratt, "Capturability-based analysis and cont of legged locomotion, Part 1: Theory and application to three simple gait models," *Int. J. Robot. Re* vol. 31, no. 9, pp. 1094–1113, Jul. 2012. doi: 10.1177/0278364912452673

[56] M. Thor, T. Kulvicius, and P. Manoonpong, "Generic neural locomotion control framework for legged robots," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 32, no. 9, pp. 4013–4025, Sept. 2021. doi: 10.1109/TNNLS.2020.3016523

[57] F. Zhang and Y. Demiris, "Learning garment manipulation policies toward robot-assisted dressing," *Sci. Robot.*, vol. 7, no. 65, p. eabm6010, Apr. 2022. doi: 10.1126/scirobotics.abm6010

[58] J. Silvério, S. Calinon, L. Rozo, and D. G. Caldwell, "Learning task priorities from demonstrations," *IEEE Trans. Robot.*, vol. 35, no. 1, pp. 78–94, Feb. 2019. doi: 10.1109/TRO.2018.2878355

[59] Z. Li, K. Zhao, L. Zhang, X. Wu, T. Zhang, Q. Li, X. Li, and C.-Y. Su, "Human-in-the-loop contro of a wearable lower limb exoskeleton for stable dynamic walking," *IEEE/ASME Trans. Mechatron* vol. 26, no. 5, pp. 2700–2711, Oct. 2021. doi: 10.1109/TMECH.2020.3044289

[60] X. Wu and Z. Li, "Cooperative manipulation of wearable dual-arm exoskeletons using force communication between partners," *IEEE Trans. Ind. Electron.*, vol. 67, no. 8, pp. 6629–6638, Aug 2020. doi: 10.1109/TIE.2019.2937036

[61] G. Li, Z. Li, and Z. Kan, "Assimilation control of a robotic exoskeleton for physical human-robot interaction," *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 2977–2984, Apr. 2022. doi: 10.1109/LRA.2022.3144537

[62] Y. Kusuda, "The humanoid robot scene in Japan," *Ind. Robot*, vol. 29, no. 5, pp. 412–419, Oct. 2002. doi: 10.1108/01439910210440219

[63] H. Niwa, K. Kodaka, Y. Sakamoto, M. Otake, S. Kawaguchi, K. Fujii, Y. Kanemori, and S. Sugan "GPS-based indoor positioning system with multi-channel pseudolite," in *Proc. IEEE Int. Conf. Robotics and Automation*, Pasadena, USA, 2008, pp. 905–910.

[64] S. Sugano and Y. Shirai, "Robot design and environment design – Waseda robot-house project," in *Proc. SICE-ICASE Int. Joint Conf.*, Busan, South Korea, 2006, pp. I-31–I-34.

[65] Y. Ogura, H. Aikawa, K. Shimomura, H. Kondo, A. Morishima, H.-O. Lim, and A. Takanishi, "Development of a new humanoid robot WABIAN-2," in *Proc. IEEE Int. Conf. Robotics and Automation*, Orlando, USA, 2006, pp. 76–81.

[66] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, and T. Isozur "Humanoid robot HRP-2," in *Proc. IEEE Int. Conf. Robotics and Automation*, New Orleans, USA, 2004, pp. 1083–1090.

[67] S. Caron, A. Kheddar, and O. Tempier, "Stair climbing stabilization of the HRP-4 humanoid robot using whole-body admittance control," in *Proc. IEEE Int. Conf. Robotics and Automation*, Montre Canada, 2019, pp. 277–283.

[68] S. Kajita, K. Kaneko, F. Kaneiro, K. Harada, M. Morisawa, S. Nakaoka, K. Miura, K. Fujiwara, E. Neo, I. Hara, K. Yokoi, and H. Hirukawa, "Cybernetic human HRP-4C: A humanoid robot with human-like proportions," in *Robotics Research: The 14th International Symposium ISRR*, C. Pradalier, R. Siegwart, and G. Hirzinger, Eds. Berlin, Heidelberg, Germany: Springer, 2011, pp. 30 314.

[69] K. Kaneko, H. Kaminaga, T. Sakaguchi, S. Kajita, M. Morisawa, I. Kumagai, and F. Kanehiro, "Humanoid robot HRP-5P: An electrically actuated humanoid robot with high-power and wide-ran joints," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1431–1438, Apr. 2019. doi: 10.1109/LRA.2019.2896465

[70] T. Kozuki, H. Mizoguchi, Y. Asano, M. Osada, T. Shirai, U. Junichi, Y. Nakanishi, K. Okada, and Inaba, "Design methodology for the thorax and shoulder of human mimetic musculoskeletal humanoid Kenshiro –A thorax structure with Rib like surface–," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Vilamoura-Algarve, Portugal, 2012, pp. 3687–3692.

[71] T. Kozuki, Y. Motegi, T. Shirai, Y. Asano, J. Urata, Y. Nakanishi, K. Okada, and M. Inaba, "Desig of upper limb by adhesion of muscles and bones–Detail human mimetic musculoskeletal humanoid Kenshiro," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Tokyo, Japan, 2013, pp. 935–940.

[72] Y. Nakanishi, Y. Asano, T. Kozuki, H. Mizoguchi, Y. Motegi, M. Osada, T. Shirai, J. Urata, K. Okada, and M. Inaba, "Design concept of detail musculoskeletal humanoid "Kenshiro"–Toward a r human body musculoskeletal simulator," in *Proc. 12th IEEE-RAS Int. Conf. Humanoid Robots*, Osaka, Japan, 2012, pp. 1–6.

[73] T. Takenaka, "The control system for the Honda humanoid robot," *Age Ageing*, vol. 35, no. S2, pp ii24–ii26, Sept. 2006.

[74] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The development of Honda humanoid robot," in *Proc. IEEE Int. Conf. Robotics and Automation*, Leuven, Belgium, 1998, pp. 1321–1326.

[75] K. Hirai, "The Honda humanoid robot: Development and future perspective," *Ind. Robot*, vol. 26, r 4, pp. 260–266, Jun. 1999. doi: 10.1108/01439919910277431

[76] J. Chestnutt, M. Lau, G. Cheung, J. Kuffner, J. Hodgins, and T. Kanade, "Footstep planning for the Honda ASIMO humanoid," in *Proc. IEEE Int. Conf. Robotics and Automation*, Barcelona, Spain, 2005, pp. 629–634.

[77] A. Austermann, S. Yamada, K. Funakoshi, and M. Nakano, "Similarities and differences in users' interaction with a humanoid and a pet robot," in *Proc. 5th ACM/IEEE Int. Conf. Human-Robot Interaction*, Osaka, Japan, 2010, pp. 73–74.

[78] J. Chestnutt, P. Michel, J. Kuffner, and T. Kanade, "Locomotion among dynamic obstacles for the Honda ASIMO," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, San Diego, USA, 2007, pp. 2578–2579.

[79] V. Ng-Thow-Hing, J. Lim, J. Wormer, R. K. Sarvadevabhatla, C. Rocha, K. Fujimura, and Y. Sakagami, "The memory game: Creating a human-robot interactive scenario for ASIMO," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Nice, France, 2008, pp. 779–786.

[80] S. Y. Okita, V. Ng-Thow-Hing, and R. Sarvadevabhatla, "Learning together: ASIMO developing a interactive learning partnership with children," in *Proc. 18th IEEE Int. Symp. Robot and Human Interactive Communication*, Toyama, Japan, 2009, pp. 1125–1130.

[81] S.-G. Roh, K. W. Yang, J. H. Park, H. Moon, H.-S. Kim, H. Lee, and H. R. Choi, “A modularized personal robot DRP I: Design and implementation,” *IEEE Trans. Robot.*, vol. 25, no. 2, pp. 414–42 Apr. 2009. doi: 10.1109/TRO.2009.2014499

[82] M. A. Diffler, E. L. Huber, C. J. Culbert, R. O. Ambrose, and W. J. Bluethmann, “Human-robot control strategies for the NASA/DARPA Robonaut,” in *Proc. IEEE Aerospace Conf.*, Big Sky, US 2003, pp. 3939–3947.

[83] M. A. Diftler, C. J. Culbert, R. O. Ambrose, R. Platt, and W. J. Bluethmann, “Evolution of the NASA/DARPA Robonaut control system,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Taipei, China, 2003, pp. 2543–2548.

[84] M. A. Diftler, J. S. Mehling, M. E. Abdallah, N. A. Radford, L. B. Bridgwater, A. M. Sanders, R. S Askew, D. M. Linn, J. D. Yamokoski, F. A. Permenter, B. K. Hargrave, R. Platt, R. T. Savely, and O. Ambrose, “Robonaut 2–The first humanoid robot in space,” in *IEEE Proc. Int. Conf. Robotics a Automation*, Shanghai, China, 2011, pp. 2178–2183.

[85] W. Bluethmann, R. Ambrose, M. Diftler, S. Askew, E. Huber, M. Goza, F. Rehnmark, C. Lovchik, and D. Magruder, “Robonaut: A robot designed to work with humans in space,” *Auton. Robot.*, vol 14, no. 2-3, pp. 179–197, Mar. 2003.

[86] G. Engelberger, “NASA’s robonaut,” *Ind. Robot*, vol. 28, no. 1, pp. 35–42, Feb. 2001. doi: 10.1108/01439910110380433

[87] Z. Li, C. Cummings, and K. Sreenath, “Animated Cassie: A dynamic relatable robotic character,” in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Las Vegas, USA, 2020, pp. 3739–374

[88] Y. Gong, R. Hartley, X. Da, A. Hereid, O. Harib, J.-K. Huang, and J. Grizzle, “Feedback control o Cassie bipedal robot: Walking, standing, and riding a Segway,” in *Proc. American Control Conf.*, Philadelphia, USA, 2019, pp. 4559–4566.

[89] N. T. Fitter and K. J. Kuchenbecker, “Designing and assessing expressive open-source faces for th Baxter robot,” in *Proc. 8th Int. Conf. Social Robotics*, Kansas City, USA, 2016, pp. 340–350.

[90] Y. Huang, X. Zhang, X. Chen, and J. Ota, “Vision-guided peg-in-hole assembly by Baxter robot,” *Adv. Mech. Eng.*, vol. 9, no. 12, Dec. 2017.

[91] Z. Ju, C. Yang, and H. Ma, “Kinematics modeling and experimental verification of Baxter robot,” in *Proc. 33rd Chinese Control Conf.*, Nanjing, China, 2014, pp. 8518–8523.

[92] L. A. Nguyen, K. D. Le, and T. L. Harman, “Kinematic redundancy resolution for Baxter robot,” in *Proc. 7th Int. Conf. Automation, Robotics and Applications*, Prague, Czech Republic, 2021, pp. 9.

[93] J. Pratt, T. Koolen, T. de Boer, J. Rebula, S. Cotton, J. Carff, M. Johnson, and P. Neuhaus, “Capturability-based analysis and control of legged locomotion, Part 2: Application to M2V2, a lower-body humanoid,” *Int. J. Robot. Res.*, vol. 31, no. 10, pp. 1117–1133, Aug. 2012. doi: 10.1177/0278364912452762

[94] J. Pratt and B. Krupp, “Design of a bipedal walking robot,” in *Proc. SPIE 6962, Unmanned System Technology X*, Orlando, USA, 2008, pp. 69621F.

[95] J. M. Garcia-Haro, E. D. Oña, J. Hernandez-Vicen, S. Martinez, and C. Balaguer, "Service robots i catering applications: A review and future challenges," *Electronics*, vol. 10, no. 1, p. 47, Jan. 2021

[96] M. Fallon, "Perception and estimation challenges for humanoid robotics: DARPA robotics challen and NASA Valkyrie," in *Proc. SPIE 9986, Unmanned/Unattended Sensors and Sensor Networks X* Edinburgh, UK, 2016, pp. 998602.

[97] M. Johnson, B. Shrewsbury, S. Bertrand, T. Wu, D. Duran, M. Floyd, P. Abeles, D. Stephen, N. Mertins, A. Lesman, J. Carff, W. Rifenburgh, P. Kaveti, W. Straatman, J. Smith, M. Griffioen, B. Layton, T. de Boer, T. Koolen, P. Neuhaus, and J. Pratt, "Team IHMC's lessons learned from the DARPA robotics challenge trials," *J. Field Robot.*, vol. 32, no. 2, pp. 192–208, Mar. 2015. doi: 10.1002/rob.21571

[98] T. Koolen, J. Smith, G. Thomas, S. Bertrand, J. Carff, N. Mertins, D. Stephen, P. Abeles, J. Englsberger, S. McCrory, J. van Egmond, M. Griffioen, M. Floyd, S. Kobus, N. Manor, S. Alsheik D. Duran, L. Bunch, E. Morphis, L. Colasanto, K.-L. H. Hoang, B. Layton, P. Neuhaus, M. Johnso and J. Pratt, "Summary of team IHMC's virtual robotics challenge entry," in *Proc. 13th IEEE-RAS Int. Conf. Humanoid Robots*, Atlanta, USA, 2013, pp. 307–314.

[99] K. Kojima, T. Sato, A. Schmitz, H. Arie, H. Iwata, and S. Sugano, "Sensor prediction and grasp stability evaluation for in-hand manipulation," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Tokyo, Japan, 2013, pp. 2479–2484.

[100] K. Nishiwaki, J. Kuffner, S. Kagami, M. Inaba, and H. Inoue, "The experimental humanoid robot H A research platform for autonomous behaviour," *Phil. Trans. Roy. Soc. A: Math. Phys. Eng. Sci.*, v 365, no. 1850, pp. 79–107, Jan. 2007.

[101] Y. Asano, T. Kozuki, S. Ookubo, M. Kawamura, S. Nakashima, T. Katayama, I. Yanokura, T. Hiro K. Kawaharazuka, S. Makino, Y. Kakiuchi, K. Okada, and M. Inaba, "Human mimetic musculoskeletal humanoid Kengoro toward real world physically interactive actions," in *Proc. IEE RAS 16th Int. Conf. Humanoid Robots*, Cancun, Mexico, 2016, pp. 876–883.

[102] Y. Kusuda, "Toyota's violin-playing robot," *Ind. Robot*, vol. 35, no. 6, pp. 504–506, Oct. 2008. doi: 10.1108/01439910810909493

[103] S. S. Srinivasa, D. Berenson, M. Cakmak, A. Collet, M. R. Dogar, A. D. Dragan, R. A. Knepper, T Niemueller, K. Strabala, M. Vande Weghe, and J. Ziegler, "HERB 2.0: Lessons learned from developing a mobile manipulator for the home," *Proc. IEEE*, vol. 100, no. 8, pp. 2410–2428, Aug. 2012. doi: 10.1109/JPROC.2012.2200561

[104] N. A. Radford, P. Strawser, K. Hambuchen, J. S. Mehling, W. K. Verdeyen, A. S. Donnan, J. Holle J. Sanchez, V. Nguyen, L. Bridgwater, R. Berka, R. Ambrose, M. Myles Markee, N. J. Fraser-Chanpong, C. McQuin, J. D. Yamokoski, S. Hart, R. Guo, A. Parsons, B. Wightman, P. Dinh, B. Ames, C. Blakely, C. Edmondson, B. Sommers, R. Rea, C. Tobler, H. Bibby, B. Howard, L. Niu, A Lee, M. Conover, L. Truong, R. Reed, D. Chesney, R. Platt, G. Johnson, C.-L. Fok, N. Paine, L. Sentis, E. Cousineau, R. Sinnet, J. Lack, M. Powell, B. Morris, A. Ames, and J. Akinyode, "Valkyr NASA's first bipedal humanoid robot," *J. Field Robot.*, vol. 32, no. 3, pp. 397–419, May 2015. doi: 10.1002/rob.21560

[105] B. Akgun, M. Cakmak, J. W. Yoo, and A. L. Thomaz, "Trajectories and keyframes for kinesthetic teaching: A human-robot interaction perspective," in *Proc. 7th ACM/IEEE Int. Conf. Human-Robo Interaction*, Boston, USA, 2012, pp. 391–398.

[106] A. Parmiggiani, M. Maggiali, L. Natale, F. Nori, A. Schmitz, N. Tsagarakis, J. S. Victor, F. Becchi G. Sandini, and G. Metta, "The design of the iCub humanoid robot," *Int. J. Humanoid Robot.*, vol. no. 4, p. 1250027, Dec. 2012. doi: 10.1142/S0219843612500272

[107] F. Negrello, M. Garabini, M. G. Catalano, P. Kryczka, W. Choi, D. G. Caldwell, A. Bicchi, and N. Tsagarakis, "WALK-MAN humanoid lower body design optimization for enhanced physical performance," in *Proc. IEEE Int. Conf. Robotics and Automation*, Stockholm, Sweden, 2016, pp. 1817–1824.

[108] N. G. Tsagarakis, S. Morfey, G. M. Cerda, Z. Li, and D. G. Caldwell, "Compliant huMANoid COMAN: Optimal joint stiffness tuning for modal frequency control," in *Proc. IEEE Int. Conf. Robotics and Automation*, Karlsruhe, Germany, 2013, pp. 673–678.

[109] N. Perrin, N. Tsagarakis, and D. G. Caldwell, "Compliant attitude control and stepping strategy for balance recovery with the humanoid COMAN," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots an Systems*, Tokyo, Japan, 2013, pp. 4145–4151.

[110] T. Wimböck, D. Nenchev, A. Albu-Schäffer, and G. Hirzinger, "Experimental study on dynamic reactionless motions with DLR's humanoid robot Justin," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, St. Louis, USA, 2009, pp. 5481–5486.

[111] K. Berns, T. Asfour, and R. Dillmann, "Design and control of the humanoid robot ARMAR," in *Romansy 13: Theory and Practice of Robots and Manipulators*, A. Morecki, G. Bianchi, and C. Rzymkowski, Eds. Vienna, Austria: Springer, 2000, pp. 307–312.

[112] I. M. Verner, A. Polishuk, and N. Krayner, "Science class with RoboThespian: Using a robot teach to make science fun and engage students," *IEEE Robot. Autom. Mag.*, vol. 23, no. 2, pp. 74–80, Ju 2016. doi: 10.1109/MRA.2016.2515018

[113] R. Tellez, F. Ferro, S. Garcia, E. Gomez, E. Jorge, D. Mora, D. Pinyol, J. Oliver, O. Torres, J. Velazquez, and D. Faconti, "Reem-B: An autonomous lightweight human-size humanoid robot," in *Proc. 8th IEEE/RAS Int. Conf. Humanoid Robots*, Daejeon, South Korea, 2008, pp. 477–483.

[114] D. J. Agravante, J. Pagès, and F. Chaumette, "Visual servoing for the REEM humanoid robot's upp body," in *Proc. IEEE Int. Conf. Robotics and Automation*, Karlsruhe, Germany, 2013, pp. 5253–5258.

[115] B. G. Draghici, A. E. Dobre, M. Misaros, and O. P. Stan, "Development of a human service robot application using pepper robot as a museum guide," in *Proc. IEEE Int. Conf. Automation, Quality Testing, Robotics*, Cluj-Napoca, Romania, 2022, pp. 127–131.

[116] A. Gardecki and M. Podpora, "Experience from the operation of the pepper humanoid robots," in *Proc. Progress in Applied Electrical Engineering*, Koscielisko, Poland, 2017, pp. 1–6.

[117] N. Igo, D. Fujita, R. Yamamoto, T. Satake, S. Mitsui, T. Kanno, and K. Hoshino, "Extended movement unit capable of moving rough terrain for pepper," in *Proc. Int. Conf. Computing and Artificial Intelligence*, Chengdu, China, 2018, pp. 112–117.

[118] K. Kawasugi, T. Yoshino, Y. Nakauchi, and Y. Anzai, “Romeo: Robot-mediated cooperative work for handling 3-dimensional physical objects,” in *Proc. 5th Int. Conf. Human-Computer Interaction*, Orlando, USA, 1993, pp. 567–572.

[119] I. Baturone, F. J. Moreno-Velo, S. Sanchez-Solano, R. M. de Agar, and A. Ollero, “Automatic desi of fuzzy control systems for autonomous mobile robots,” in *Proc. 28th Annu. Conf. Industrial Electronics Society*, Seville, Spain, 2002, pp. 2451–2456.

[120] A. Kalouguine, V. De-León-Gómez, C. Chevallereau, S. Dalibard, and Y. Aoustin, “A new human like walking for the humanoid robot Romeo,” *Multibody Syst. Dyn.*, vol. 53, no. 4, pp. 411–434, N 2021. doi: 10.1007/s11044-021-09805-w

[121] T. Jung, J. Lim, H. Bae, K. K. Lee, H.-M. Joe, and J.-H. Oh, “Development of the humanoid disast response platform DRC-HUBO+,” *IEEE Trans. Robot.*, vol. 34, no. 1, pp. 1–17, Feb. 2018. doi: 10.1109/TRO.2017.2776287

[122] Z. Yu, Q. Huang, G. Ma, X. Chen, W. Zhang, J. Li, and J. Gao, “Design and development of the humanoid robot BHR-5,” *Adv. Mech. Eng.*, vol. 6, no. 8, Jan. 2014.

[123] Y. Liu and L. Liu, “Accurate real-time ball trajectory estimation with onboard stereo camera syster for humanoid Ping-Pong robot,” *Robot. Auton. Syst.*, vol. 101, pp. 34–44, Mar. 2018. doi: 10.1016/j.robot.2017.12.004

[124] Q. Xie, Y. Liu, R. Xiong, and J. Chu, “Real-time accurate ball trajectory estimation with ”asynchronous” stereo camera system for humanoid Ping-Pong robot,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Hong Kong, China, 2014, pp. 6212–6217.

[125] L. Liu, J. S. Wang, K. Chen, J. D. Zhao, D. C. Yang, and B. I. T. Bit, “The biped humanoid robot THBIP-1,” in *Proc. Int. Workshop on Bio-Robotics and Teleoperation*, 2001, pp. 164–167.

[126] I. Ha, Y. Tamura, and H. Asama, “Development of open platform humanoid robot DARwIn-OP,” *Adv. Robot.*, vol. 27, no. 3, pp. 223–232, Feb. 2013. doi: 10.1080/01691864.2012.754079

[127] D. Gouaillier, V. Hugel, P. Blazevic, C. Kilner, J. Monceaux, P. Lafourcade, B. Marnier, J. Serre, a B. Maisonnier, “Mechatronic design of NAO humanoid,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Kobe, Japan, 2009, pp. 769–774.

[128] M. Lapeyre, S. N’Guyen, A. Le Falher, and P.-Y. Oudeyer, “Rapid morphological exploration with the Poppy humanoid platform,” in *Proc. IEEE-RAS Int. Conf. Humanoid Robots*, Madrid, Spain, 2014, pp. 959–966.

[129] D. Popov, A. Klimchik, and I. Afanasyev, “Design and stiffness analysis of 12 DoF poppy-inspirec humanoid,” in *Proc. 14th Int. Conf. Informatics in Control, Automation and Robotics*, Madrid, Spa 2017, pp. 66–78.

[130] P. Allgeuer, H. Farazi, M. Schreiber, and S. Behnke, “Child-sized 3D printed igus humanoid open platform,” in *Proc. IEEE-RAS 15th Int. Conf. Humanoid Robots*, Seoul, South Korea, 2015, pp. 33-40.

[131] S. Saeedvand, H. S. Aghdasi, and J. Baltes, “Novel lightweight odometric learning method for humanoid robot localization,” *Mechatronics*, vol. 55, pp. 38–53, Nov. 2018. doi: 10.1016/j.mechatronics.2018.08.007

[132] A. Nikkhah, A. Yousefi-Koma, R. Mirjalili, and H. M. Farimani, “Design and implementation of small-sized 3D printed Surena-Mini humanoid platform,” in *Proc. 5th RSI Int. Conf. Robotics and Mechatronics*, Tehran, Iran, 2017, pp. 132–137.

[133] G. Ficht, H. Farazi, A. Brandenburger, D. Rodriguez, D. Pavlichenko, P. Allgeuer, M. Hosseini, an S. Behnke, “NimbRo-OP2X: Adult-sized open-source 3D printed humanoid robot,” in *Proc. IEEE-RAS 18th Int. Conf. Humanoid Robots*, Beijing, China, 2018, pp. 747–754.

[134] G. Ficht, H. Farazi, D. Rodriguez, D. Pavlichenko, P. Allgeuer, A. Brandenburger, and S. Behnke, “Nimbro-OP2X: Affordable adult-sized 3D-printed open-source humanoid robot for research,” *Int. Humanoid Robot.*, vol. 17, no. 5, p. 2050021, Oct. 2020. doi: 10.1142/S0219843620500218

[135] S. Lohmeier, T. Buschmann, and H. Ulbrich, “Humanoid robot LOLA,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Kobe, Japan, 2009, pp. 2516–2521.

[136] F. Ferland, A. Aumont, D. Létourneau, M.-A. Legault, and F. Michaud, “Johnny-0, a compliant, force-controlled and interactive humanoid autonomous robot,” in *Proc. 7th ACM/IEEE Int. Conf. Human-Robot Interaction*, Boston, USA, 2012, pp. 417–417.

[137] R. S. N. Cruz and J. M. Ibarra Zannatha, “Optimal design for a humanoid robot based on passive dynamic walkers and genetic algorithms,” in *Proc. 12th Int. Conf. Electrical Engineering, Comput Science and Automatic Control*, Mexico City, Mexico, 2015, pp. 1–6.

[138] J. Englsberger, A. Werner, C. Ott, B. Henze, M. A. Roa, G. Garofalo, R. Burger, A. Beyer, O. Eiberger, K. Schmid, and A. Albu-Schäffer, “Overview of the torque-controlled humanoid robot TORO,” in *Proc. IEEE-RAS Int. Conf. Humanoid Robots*, Madrid, Spain, 2014, pp. 916–923.

[139] T. Osawa, T. Ogawa, and T. Nakamura, “Path planning with robot’s transformation for traveling-wave-type mobile robot (TORO-IV),” in *Proc. 15th Int. Conf. Climbing and Walking Robots and t Support Technologies for Mobile Machines*, Baltimore, USA, 2012, pp. 199–206.

[140] S. Marchesi, D. Ghiglino, F. Ciardo, J. Perez-Osorio, E. Baykara, and A. Wykowska, “Do we adop the intentional stance toward humanoid robots?” *Front. Psychol.*, vol. 10, p. 450, Feb. 2019. doi: 10.3389/fpsyg.2019.00450

[141] A. Laurenzi, D. Kanoulas, E. M. Hoffman, L. Muratore, and N. G. Tsagarakis, “Whole-body stabilization for visual-based box lifting with the COMAN+ robot,” in *Proc. 3rd IEEE Int. Conf. Robotic Computing*, Naples, Italy, 2019, pp. 445–446.

[142] J. Lee, H. Dallali, N. Tsagarakis, and D. Caldwell, “Robust and model-free link position tracking control for humanoid COMAN with multiple compliant joints,” in *Proc. 13th IEEE-RAS Int. Conf. Humanoid Robots*, Atlanta, USA, 2013, pp. 1–7.

[143] R. Van Ham, B. Verrelst, B. Vanderborght, F. Daerden, and D. Lefeber, “Experimental results on t first movements of the pneumatic biped “Lucy”,” in *Proc. 6th Int. Conf. Climbing and Walking Robots and the Support Technologies for Mobile Machines*, Catania, Italy, 2003, pp. 485–492.

[144] J.-Y. Kim, I.-W. Park, J. Lee, M.-S. Kim, B.-K. Cho, and J.-H. Oh, “System design and dynamic walking of humanoid robot KHR-2,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Barcelona Spain, 2005, pp. 1431–1436.

[145] J.-Y. Kim, I.-W. Park, J. Lee, and J.-H. Oh, “Experiments of vision guided walking of humanoid robot, KHR-2,” in *Proc. 5th IEEE-RAS Int. Conf. Humanoid Robots*, Tsukuba, Japan, 2005, pp. 13 140.

[146] I.-W. Park, J.-Y. Kim, J. Lee, and J.-H. Oh, “Mechanical design of humanoid robot platform KHR- (KAIST humanoid robot 3: HUBO),” in *Proc. 5th IEEE-RAS Int. Conf. Humanoid Robots*, Tsukub Japan, 2005, pp. 321–326.

[147] I.-W. Park, J.-Y. Kim, and J.-H. Oh, “Online walking pattern generation and its application to a bip humanoid robot – KHR-3 (HUBO),” *Adv. Robot.*, vol. 22, no. 2-3, pp. 159–190, Mar. 2008. doi: 10.1163/156855308X292538

[148] G. Wang, Q. Huang, J. Geng, H. Deng, and K. Li, “Cooperation of dynamic patterns and sensory reflex for humanoid walking,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Taipei, China, 2003, pp. 2472–2477.

[149] B. Cao, Y. Gu, K. Sun, M. Jin, and H. Liu, “Development of HIT humanoid robot,” in *Proc. 10th I Conf. Intelligent Robotics and Applications*, Wuhan, China, 2017, pp. 286–297.

[150] Z. Shi, W. Xu, X. Wen, and P. Jiang, “Distributed hierarchical control system of humanoid robot THBIP-1,” in *Proc. 4th World Congr. Intelligent Control and Automation*, Shanghai, China, 2002, pp. 1265–1269.

[151] Z. Xia, K. Chen, and Y. He, “Modeling and motion planning of the infant-size humanoid robot THBIP-II,” in *Proc. 7th IEEE-RAS Int. Conf. Humanoid Robots*, Pittsburgh, USA, 2007, pp. 577–582.

[152] Z. Xia, L. Liu, J. Xiong, Q. Yi, and K. Chen, “Design aspects and development of humanoid robot THBIP-2,” *Robotica*, vol. 26, no. 1, pp. 109–116, Jan. 2008. doi: 10.1017/S0263574707003645

[153] J. Murphy, U. Gretzel, and J. Pesonen, “Marketing robot services in hospitality and tourism: The ro of anthropomorphism,” *J. Travel Tourism Mark.*, vol. 36, no. 7, pp. 784–795, Feb. 2019. doi: 10.1080/10548408.2019.1571983

[154] U. Gupta, L. Qin, Y. Wang, H. Godaba, and J. Zhu, “Soft robots based on dielectric elastomer actuators: A review,” *Smart Mater. Struct.*, vol. 28, no. 10, p. 103002, Sept. 2019. doi: 10.1088/13 665X/ab3a77

[155] T.-Y. Huang, H.-W. Huang, D. D. Jin, Q. Y. Chen, J. Y. Huang, L. Zhang, and H. L. Duan, “Four-dimensional micro-building blocks,” *Sci. Adv.*, vol. 6, no. 3, p. eaav8219, Jan. 2020. doi: 10.1126/sciadv.aav8219

[156] Y. Sun, H. Tang, Y. Tang, J. Zheng, D. Dong, X. Chen, F. Liu, L. Bai, W. Ge, L. Xin, H. Pu, Y. Peng, and J. Luo, “Review of recent progress in robotic knee prosthesis related techniques: Structu actuation and control,” *J. Bionic Eng.*, vol. 18, no. 4, pp. 764–785, Aug. 2021. doi: 10.1007/s4223 021-0065-4

[157] I. Kotseruba and J. K. Tsotsos, “40 years of cognitive architectures: Core cognitive abilities and practical applications,” *Artif. Intell. Rev.*, vol. 53, no. 1, pp. 17–94, Jan. 2020. doi: 10.1007/s10462 018-9646-y

[158] F. McLeay, V. S. Osburg, V. Yoganathan, and A. Patterson, "Replaced by a robot: Service implications in the age of the machine," *J. Ser. Res.*, vol. 24, no. 1, pp. 104–121, Feb. 2021. doi: 10.1177/1094670520933354

[159] C. Yang, Y. Jiang, J. Na, Z. Li, L. Cheng, and C.-Y. Su, "Finite-time convergence adaptive fuzzy control for dual-arm robot with unknown kinematics and dynamics," *IEEE Trans. Fuzzy Syst.*, vol. 27, no. 3, pp. 574–588, Mar. 2019. doi: 10.1109/TFUZZ.2018.2864940

[160] I. P. I. Pappas, M. R. Popovic, T. Keller, V. Dietz, and M. Morari, "A reliable gait phase detection system," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 9, no. 2, pp. 113–125, Jun. 2001. doi: 10.1109/7333.928571

[161] K. Wampler and Z. Popović, "Optimal gait and form for animal locomotion," *ACM Trans. Graph.*, vol. 28, no. 3, p. 60, Aug. 2009.

[162] H. Knuesel, H. Geyer, and A. Seyfarth, "Influence of swing leg movement on running stability," *Hum. Mov. Sci.*, vol. 24, no. 4, pp. 532–543, Aug. 2005. doi: 10.1016/j.humov.2005.08.0

[163] J. Allali, R. Fabre, L. Gondry, L. Hofer, O. Ly, S. N'Guyen, G. Passault, A. Pirrone, and Q. Rouxe "Rhoban football club: RoboCup humanoid kid-size 2017 champion team paper," in *RoboCup 201 Robot World Cup XXI*, H. Akiyama, O. Obst, C. Sammut, and F. Tonidandel, Eds. Cham, Germany Springer, 2018, pp. 423–434.

[164] A. Mejias, R. S. Herrera, and M. A. Márquez, A. J. Calderón, I. Gonzalez, and J. M. Andújar, "Eas handling of sensors and actuators over TCP/IP networks by open source hardware/software," *Sens* vol. 17, no. 1, p. 94, Jan. 2017. doi: 10.3390/s17010094

[165] Y. Almubarak and Y. Tadesse, "Design and motion control of bioinspired humanoid robot head fro servo motors toward artificial muscles," in *Proc. SPIE 10163, Electroactive Polymer Actuators an Devices*, Portland, USA, 2017, pp. 101631U.

[166] A. M. Al-Busaidi, "Dvelopment of an educational environment for online control of a biped robot using MATLAB and Arduino," in *Proc. 9th France-Japan & 7th Europe-Asia Congr. Mechatronics/13th Int. Workshop on Research and Education in Mechatronics*, Paris, France, 201 pp. 337–344.

[167] M. W. Spong, "An historical perspective on the control of robotic manipulators," *Annu. Rev. Contr Robot. Auton. Syst.*, vol. 5, pp. 1–31, May 2022. doi: 10.1146/annurev-control-042920-094829

[168] J. Yamaguchi, E. Soga, S. Inoue, and A. Takanishi, "Development of a bipedal humanoid robot-control method of whole body cooperative dynamic biped walking," in *Proc. IEEE Int. Conf. Robotics and Automation*, Detroit, USA, 1999, pp. 368–374.

[169] T. Sugihara, Y. Nakamura, and H. Inoue, "Real-time humanoid motion generation through ZMP manipulation based on inverted pendulum control," in *Proc. IEEE Int. Conf. Robotics and Automation*, Washington, USA, 2002, pp. 1404–1409.

[170] C. Tao, J. Xue, Z. Zhang, F. Cao, C. Li, and H. Gao, "Gait optimization method for humanoid robo based on parallel comprehensive learning particle swarm optimizer algorithm," *Front. Neurorobot.* vol. 14, p. 600885, Jan. 2021. doi: 10.3389/fnbot.2020.600885

[171] T. T. Huan, K. B. Thy, N. H. H. Trung, and H. P. H. Anh, "Stable gait optimization for small-sized humanoid robot using CFO," in *Proc. 15th Int. Conf. Control, Automation, Robotics and Vision*, Singapore, Singapore, 2018, pp. 436–441.

[172] J. H. Choe, J.-H. Kim, S. Hong, J. Lee, and H.-W. Park, "Seamless reaction strategy for bipedal locomotion exploiting real-time nonlinear model predictive control," *IEEE Robot. Autom. Lett.*, vo 8, no. 8, pp. 5031–5038, Aug. 2023. doi: 10.1109/LRA.2023.3291273

[173] W. Ke, Y. Bai, H. Li, K. Chen, and Q. Yuan, "Control of stepping downstairs for humanoid robot based on dynamic multi-objective optimization," *Concurrency Comput.: Pract. Exper.*, vol. 33, no. p. e5999, Mar. 2021. doi: 10.1002/cpe.5999

[174] Y. Yoshida, K. Takeuchi, D. Sato, and D. Nenchev, "Balance control of humanoid robots in respor to disturbances in the frontal plane," in *Proc. IEEE Int. Conf. Robotics and Biomimetics*, Karon Beach, Thailand, 2011, pp. 2241–2242.

[175] J. W. Kim, T. T. Tran, C. Van Dang, and B. Kang, "Motion and walking stabilization of humanoid using sensory reflex control," *Int. J. Adv. Robot. Syst.*, vol. 13, no. 2, p. 77, Mar.–Apr. 2016. doi: 10.5772/63116

[176] K. Seo, J. Kim, and K. Roh, "Towards natural bipedal walking: Virtual gravity compensation and capture point control," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Vilamoura-Algarve, Portugal, 2012, pp. 4019–4026.

[177] M. C. Capolei, E. Angelidis, E. Falotico, H. H. Lund, and S. Tolu, "A biomimetic control method increases the adaptability of a humanoid robot acting in a dynamic environment," *Front. Neurorob* vol. 13, p. 70, Aug. 2019. doi: 10.3389/fnbot.2019.00070

[178] M. Sharifi, J. K. Mehr, V. K. Mushahwar, and M. Tavakoli, "Adaptive CPG-based gait planning w learning-based torque estimation and control for exoskeletons," *IEEE Robot. Autom. Lett.*, vol. 6, n 4, pp. 8261–8268, Oct. 2021. doi: 10.1109/LRA.2021.3105996

[179] D. Ferigo, R. Camoriano, P. M. Viceconte, D. Calandriello, S. Traversaro, L. Rosasco, and D. Pucc "On the emergence of whole-body strategies from humanoid robot push-recovery learning," *IEEE Robot. Autom. Lett.*, vol. 6, no. 4, pp. 8561–8568, Oct. 2021. doi: 10.1109/LRA.2021.3076955

[180] D. Luo, X. Han, Y. Ding, Y. Ma, Z. Liu, and X. Wu, "Learning push recovery for a bipedal human robot with dynamical movement primitives," in *Proc. IEEE-RAS 15th Int. Conf. Humanoid Robots* Seoul, South Korea, 2015, pp. 1013–1019.

[181] P. M. Viceconte, R. Camoriano, G. Romualdi, D. Ferigo, S. Dafarra, S. Traversaro, G. Oriolo, L. Rosasco, and D. Pucci, "ADHERENT: Learning human-like trajectory generators for whole-body control of humanoid robots," *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 2779–2786, Apr. 2022. doi: 10.1109/LRA.2022.3141658

[182] M. Mowbray, R. Smith, E. A. Del Rio-Chanona, and D. Zhang, "Using process data to generate an optimal control policy via apprenticeship and reinforcement learning," *AIChE J.*, vol. 67, no. 9, p. e17306, Sept. 2021. doi: 10.1002/aic.17306

[183] J. Pratt, J. Carff, S. Drakunov, and A. Goswami, "Capture point: A step toward humanoid push recovery," in *Proc. 6th IEEE-RAS Int. Conf. Humanoid Robots*, Genova, Italy, 2006, pp. 200–207.

[184] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, "Biped walking pattern generation by using preview control of zero-moment point," in *Proc. IEEE Int. Co Robotics and Automation*, Taipei, China, 2003, pp. 1620–1626.

[185] K. Yamamoto, T. Kamioka, and T. Sugihara, "Survey on model-based biped motion control for humanoid robots," *Adv. Robot.*, vol. 34, no. 21–22, pp. 1353–1369, Nov. 2020. doi: 10.1080/01691864.2020.1837670

[186] P. Mishra, U. Jain, S. Choudhury, S. Singh, A. Pandey, A. Sharma, R. Singh, V. K. Pathak, K. K. Saxena, and A. Gehlot, "Footstep planning of humanoid robot in ROS environment using generativ adversarial networks (GANs) deep learning," *Robot. Auton. Syst.*, vol. 158, p. 104269, Dec. 2022. doi: 10.1016/j.robot.2022.104269

[187] M. A. Elhosseini, A. Y. Haikal, M. Badawy, and N. Khashan, "Biped robot stability based on an A parametric whale optimization algorithm," *J. Comput. Sci.*, vol. 31, pp. 17–32, Feb. 2019. doi: 10.1016/j.jocs.2018.12.005

[188] C. Liu, T. Zhang, C. Zhang, M. Liu, and Q. Chen, "Foot placement compensator design for human walking based on discrete control lyapunov function," *IEEE Trans. Syst. Man Cybern. Syst.*, vol. 5 no. 4, pp. 2332–2341, Apr. 2021. doi: 10.1109/TSMC.2019.2912417

[189] M. Murooka, M. Morisawa, and F. Kanehiro, "Centroidal trajectory generation and stabilization based on preview control for humanoid multi-contact motion," *IEEE Robot. Autom. Lett.*, vol. 7, no 3, pp. 8225–8232, Jul. 2022. doi: 10.1109/LRA.2022.3186515

[190] K. Bergamin, S. Clavet, D. Holden, and J. R. Forbes, "DReCon: Data-driven responsive control of physics-based characters," *Acm Trans. Graph.*, vol. 38, no. 6, p. 206, Dec. 2019.

[191] J. E. Pratt and R. Tedrake, "Velocity-based stability margins for fast bipedal walking," in *Fast Motions in Biomechanics and Robotics*, M. Diehl and K. Mombaur, Eds. Berlin, Heidelberg, Germany: Springer, 2006, vol. 340, pp. 299–324.

[192] H. F. N. Al-Shuka, F. Allmendinger, B. Corves, and W.-H. Zhu, "Modeling, stability and walking pattern generators of biped robots: A review," *Robotica*, vol. 32, no. 6, pp. 907–934, Sept. 2014. doi: 10.1017/S0263574713001124

[193] M. Bjelonic, C. D. Bellicoso, Y. de Viragh, D. Sako, F. D. Tresoldi, F. Jenelten, and M. Hutter, "Keep rollin'-whole-body motion control and planning for wheeled quadrupedal robots," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 2116–2123, Apr. 2019. doi: 10.1109/LRA.2019.2899750

[194] H. Su, A. Mariani, S. E. Ovur, A. Menciassi, G. Ferrigno, and E. De Momi, "Toward teaching by demonstration for robot-assisted minimally invasive surgery," *IEEE Trans. Automat. Sci. Eng.*, vol 18, no. 2, pp. 484–494, Apr. 2021. doi: 10.1109/TASE.2020.3045655

[195] T. T. Mac, C. Copot, D. T. Tran, and R. De Keyser, "Heuristic approaches in robot path planning: A survey," *Robot. Auton. Syst.*, vol. 86, pp. 13–28, Dec. 2016. doi: 10.1016/j.robot.2016.08.001

[196] F. Martín, J. Ginés, D. Vargas, F. J. Rodríguez-Lera, and V. Matellán, "Planning topological navigation for complex indoor environments," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Madrid, Spain, 2018, pp. 8227–8232.

[197] M. Selvaggio, A. Garg, F. Ruggiero, G. Oriolo, and B. Siciliano, “Non-prehensile object transportation via model predictive non-sliding manipulation control,” *IEEE Trans. Control Syst. Technol.*, vol. 31, no. 5, pp. 2231–2244, Sept. 2023. doi: 10.1109/TCST.2023.3277224

[198] A. Meduri, P. Shah, J. Viereck, M. Khadiv, I. Havoutis, and L. Righetti, “BiConMP: A nonlinear model predictive control framework for whole body motion planning,” *IEEE Trans. Robot.*, vol. 39 no. 2, pp. 905–922, Apr. 2023. doi: 10.1109/TRO.2022.3228390

[199] C. Yang, C. Pu, G. Xin, J. Zhang, and Z. Li, “Learning complex motor skills for legged robot fall recovery,” *IEEE Robot. Autom. Lett.*, vol. 8, no. 7, pp. 4307–4314, Jul. 2023. doi: 10.1109/LRA.2023.3281290

[200] H. Qi, X. Chen, Z. Yu, G. Huang, Y. Liu, L. Meng, and Q. Huang, “Vertical jump of a humanoid robot with CoP-guided angular momentum control and impact absorption,” *IEEE Trans. Robot.*, vo 39, no. 4, pp. 3154–3166, Aug. 2023. doi: 10.1109/TRO.2023.3271136

[201] J. Ding, T. L. Lam, L. Ge, J. Pang, and Y. Huang, “Safe and adaptive 3-D locomotion via constrain task-space imitation learning,” *IEEE/ASME Trans. Mechatron.*, vol. 28, no. 6, pp. 3029–3040, Dec 2023. doi: 10.1109/TMECH.2023.3239099

[202] Z. Jiang, Y. Ma, X. Cao, M. Shen, C. Yin, H. Liu, J. Cui, Z. Sun, X. Huang, and H. Li, “FC-EODR Immersive humanoid dual-arm dexterous explosive ordnance disposal robot,” *Biomimetics*, vol. 8, 1, p. 67, Feb. 2023. doi: 10.3390/biomimetics8010067

[203] Y. Zhou, J. Zhao, P. Lu, Z. Wang, and B. He, “TacSuit: A wearable large-area, bioinspired multimodal tactile skin for collaborative robots,” *IEEE Trans. Ind. Electron.*, vol. 71, no. 2, pp. 170 1717, Feb. 2024. doi: 10.1109/TIE.2023.3253921

[204] S. Pohtongkam and J. Srinonchat, “Object recognition for humanoid robots using full hand tactile sensor,” *IEEE Access*, vol. 11, pp. 20284–20297, Feb. 2023. doi: 10.1109/ACCESS.2023.3249573

[205] Y. Qin, A. Escande, F. Kanehiro, and E. Yoshida, “Dual-arm mobile manipulation planning of a lo deformable object in industrial installation,” *IEEE Robot. Autom. Lett.*, vol. 8, no. 5, pp. 3039–304 May 2023. doi: 10.1109/LRA.2023.3264779

[206] J. Ramos and S. Kim, “Humanoid dynamic synchronization through whole-body bilateral feedback teleoperation,” *IEEE Trans. Robot.*, vol. 34, no. 4, pp. 953–965, Aug. 2018. doi: 10.1109/TRO.2018.2830387

[207] X. Liu, Y. Chen, J. Li, and A. Cangelosi, “Real-time robotic mirrored behavior of facial expression and head motions based on lightweight networks,” *IEEE Internet Things J.*, vol. 10, no. 2, pp. 1401 1413, Jan. 2023. doi: 10.1109/JIOT.2022.3205123

[208] S. Zhang, Y. Chen, L. Zhang, X. Gao, and X. Chen, “Study on robot grasping system of SSVEP-B based on augmented reality stimulus,” *Tsinghua Sci. Technol.*, vol. 28, no. 2, pp. 322–329, Apr. 2023. doi: 10.26599/TST.2021.9010085

[209] L. Pan, F. Wang, Y. Cheng, W. R. Leow, Y.-W. Zhang, M. Wang, P. Cai, B. Ji, D. Li, and X. Chen “A supertough electro-tendon based on spider silk composites,” *Nat. Commun.*, vol. 11, no. 1, p. 1332, Mar. 2020. doi: 10.1038/s41467-020-14988-5

[210] K. Hwang, S. W. Lee, S. W. Karng, and S. Y. Kim, "Thermal performance of non-metallic two-pha cold plates for humanoid robot cooling," in *Proc. 11th Intersociety Conf. Thermal and Thermomechanical Phenomena in Electronic Systems*, Orlando, USA, 2008, pp. 6–11.

[211] D. Chen, Q. Liu, Z. Han, J. Zhang, H. Song, K. Wang, Z. Song, S. Wen, Y. Zhou, C. Yan, and Y. S "4D printing strain self-sensing and temperature self-sensing integrated sensor-actuator with bioinspired gradient gaps," *Adv. Sci.*, vol. 7, no. 13, p. 20005484, Jul. 2020.

[212] Y. Ma, D. Xu, and F. Qin, "Efficient insertion control for precision assembly based on demonstrati learning and reinforcement learning," *IEEE Trans. Ind. Inf.*, vol. 17, no. 7, pp. 4492–4502, Jul. 2021. doi: 10.1109/TII.2020.3020065

[213] N. Wang, C. Chen, and C. Yang, "A robot learning framework based on adaptive admittance contr and generalizable motion modeling with neural network controller," *Neurocomputing*, vol. 390, pp 260–267, May 2020. doi: 10.1016/j.neucom.2019.04.100

[214] H. Huang, T. Zhang, C. Yang, and C. L. P. Chen, "Motor learning and generalization using broad learning adaptive neural control," *IEEE Trans. Ind. Electron.*, vol. 67, no. 10, pp. 8608–8617, Oct. 2020. doi: 10.1109/TIE.2019.2950853

[215] C. L. P. Chen and Z. Liu, "Broad learning system: An effective and efficient incremental learning system without the need for deep architecture," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 29, no pp. 10–24, Jan. 2018. doi: 10.1109/TNNLS.2017.2716952

[216] M. Andrychowicz, B. Baker, M. Chociej, R. Józefowicz, B. McGrew, J. Pachocki, A. Petron, M. Plappert, G. Powell, A. Ray, J. Schneider, S. Sidor, J. Tobin, P. Welinder, L. Weng, and W. Zarem "Learning dexterous in-hand manipulation," *Int. J. Robot. Res.*, vol. 39, no. 1, pp. 3–20, Jan. 2020. doi: 10.1177/0278364919887447

[217] S. Kamio and H. Iba, "Adaptation technique for integrating genetic programming and reinforcemen learning for real robots," *IEEE Trans. Evol. Computat.*, vol. 9, no. 3, pp. 318–333, Jun. 2005. doi: 10.1109/TEVC.2005.850290

[218] L. Hu, C. Zhou, and Z. Sun, "Estimating biped gait using spline-based probability distribution function with Q-learning," *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1444–1452, Mar. 2008. doi: 10.1109/TIE.2007.908526

[219] H. Su, W. Qi, Y. Hu, H. R. Karimi, G. Ferrigno, and E. De Momi, "An incremental learning framework for human-like redundancy optimization of anthropomorphic manipulators," *IEEE Tran Ind. Inf.*, vol. 18, no. 3, pp. 1864–1872, Mar. 2022. doi: 10.1109/TII.2020.3036693

[220] O. Kroemer, S. Niekum, and G. Konidaris, "A review of robot learning for manipulation: Challeng representations, and algorithms," *J. Mach. Learn. Res.*, vol. 22, no. 30, pp. 1–82, Jan. 2021.

[221] D. H. Tran, F. Hamker, and J. Nassour, "A humanoid robot learns to recover perturbation during swinging motion," *IEEE Trans. Syst. Man Cybern.: Syst.*, vol. 50, no. 10, pp. 3701–3712, Oct. 2020. doi: 10.1109/TSMC.2018.2884619

[222] A. Rezaeipanah, P. Amiri, and S. Jafari, "Performing the kick during walking for robocup 3D socc simulation league using reinforcement learning algorithm," *Int. J. Soc. Robot.*, vol. 13, no. 6, pp. 1235–1252, Sept. 2021. doi: 10.1007/s12369-020-00712-2

[223] K. Lobos-Tsunekawa, F. Leiva, and J. Ruiz-del-Solar, “Visual navigation for biped humanoid robo using deep reinforcement learning,” *IEEE Robot. Autom. Lett.*, vol. 3, no. 4, pp. 3247–3254, Oct. 2018. doi: 10.1109/LRA.2018.2851148

[224] T. Hester, M. Quinlan, and P. Stone, “Generalized model learning for reinforcement learning on a humanoid robot,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Anchorage, USA, 2010, pp. 2369–2374.

[225] V. Tangkaratt, J. Morimoto, and M. Sugiyama, “Model-based reinforcement learning with dimensi reduction,” *Neural Netw.*, vol. 84, pp. 1–16, Dec. 2016. doi: 10.1016/j.neunet.2016.08.005

[226] R. Lober, O. Sigaud, and V. Padois, “Task feasibility maximization using model-free policy search and model-based whole-body control,” *Front. Robot. AI*, vol. 7, p. 61, Jun. 2020. doi: 10.3389/frobt.2020.00061

[227] N. A. Hansen, H. Sun, and X. Wang, “Temporal difference learning for model predictive control,” in *Proc. 39th Int. Conf. Machine Learning*, Baltimore, USA, 2022, pp. 8387–8406.

[228] B. Ichter and M. Pavone, “Robot motion planning in learned latent spaces,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2407–2414, Jul. 2019. doi: 10.1109/LRA.2019.2901898

[229] J. Li, Z. Li, X. Li, Y. Feng, Y. Hu, and B. Xu, “Skill learning strategy based on dynamic motion primitives for human-robot cooperative manipulation,” *IEEE Trans. Cogn. Dev. Syst.*, vol. 13, no. pp. 105–117, Mar. 2021. doi: 10.1109/TCDS.2020.3021762

[230] N. Wang, C. Chen, and A. Di Nuovo, “A framework of hybrid force/motion skills learning for robots,” *IEEE Trans. Cogn. Dev. Syst.*, vol. 13, no. 1, pp. 162–170, Mar. 2021. doi: 10.1109/TCDS.2020.2968056

[231] S. Schaal, “Is imitation learning the route to humanoid robots?” *Trends Cognit. Sci.*, vol. 3, no. 6, p 233–242, Jun. 1999. doi: 10.1016/S1364-6613(99)01327-3

[232] F. Qin, D. Xu, D. Zhang, and Y. Li, “Robotic skill learning for precision assembly with microscop vision and force feedback,” *IEEE/ASME Trans. Mechatron.*, vol. 24, no. 3, pp. 1117–1128, Jun. 2019. doi: 10.1109/TMECH.2019.2909081

[233] C. Yang, C. Chen, W. He, R. Cui, and Z. Li, “Robot learning system based on adaptive neural cont and dynamic movement primitives,” *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 30, no. 3, pp. 777 787, Mar. 2019. doi: 10.1109/TNNLS.2018.2852711

[234] Y. Zhang, M. Li, and C. Yang, “Robot learning system based on dynamic movement primitives an neural network,” *Neurocomputing*, vol. 451, pp. 205–214, Sept. 2021. doi: 10.1016/j.neucom.2021.04.034

[235] Y. Wu, Y. Su, and Y. Demiris, “A morphable template framework for robot learning by demonstration: Integrating one-shot and incremental learning approaches,” *Robot. Auton. Syst.*, vol 62, no. 10, pp. 1517–1530, Oct. 2014. doi: 10.1016/j.robot.2014.05.010

[236] K. Lee, Y. Su, T.-K. Kim, and Y. Demiris, “A syntactic approach to robot imitation learning using probabilistic activity grammars,” *Robot. Auton. Syst.*, vol. 61, no. 12, pp. 1323–1334, Dec. 2013. doi: 10.1016/j.robot.2013.08.003

[237] J. Hua, L. Zeng, G. Li, and Z. Ju, “Learning for a robot: Deep reinforcement learning, imitation learning, transfer learning,” *Sensors*, vol. 21, no. 4, p. 1278, Feb. 2021. doi: 10.3390/s21041278

[238] L. R. Rabiner, “A tutorial on hidden Markov models and selected applications in speech recognition,” *Proc. IEEE*, vol. 77, no. 2, pp. 257–286, Feb. 1989. doi: 10.1109/5.18626

[239] M. Field, D. Stirling, Z. Pan, and F. Naghdy, “Learning trajectories for robot programing by demonstration using a coordinated mixture of factor analyzers,” *IEEE Trans. Cybern.*, vol. 46, no. pp. 706–717, Mar. 2016. doi: 10.1109/TCYB.2015.2414277

[240] A. J. Ijspeert, J. Nakanishi, and S. Schaal, “Movement imitation with nonlinear dynamical systems humanoid robots,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Washington, USA, 2002, pp 1398–1403.

[241] Y. Huang, L. Rozo, J. Silvério, and D. G. Caldwell, “Kernelized movement primitives,” *Int. J. Rob Res.*, vol. 38, no. 7, pp. 833–852, May 2019. doi: 10.1177/0278364919846363

[242] Z. Dong, Z. Li, Y. Yan, S. Calinon, and F. Chen, “Passive bimanual skills learning from demonstration with motion graph attention networks,” *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 4917–4923, Apr. 2022. doi: 10.1109/LRA.2022.3152974

[243] D. S. Brown and S. Niekum, “Machine teaching for inverse reinforcement learning: Algorithms an applications,” in *Proc. 33rd AAAI Conf. Artificial Intelligence*, Honolulu, USA, 2019, pp. 7749–77

[244] P. Kamalaruban, R. Devidze, V. Cevher, and A. Singla, “Interactive teaching algorithms for invers reinforcement learning,” in *Proc. 28th Int. Joint Conf. Artificial Intelligence*, Macao, China, 2019, 2692–2700.

[245] C. Tan, Y. Li, and Y. Cheng, “An inverse reinforcement learning algorithm for semi-Markov decis processes,” in *Proc. IEEE Symp. Series on Computational Intelligence*, Honolulu, USA, 2017, pp. 1256–1261.

[246] W. Huang, F. Braghin, and Z. Wang, “Learning to drive via apprenticeship learning and deep reinforcement learning,” in *Proc. IEEE 31st Int. Conf. Tools With Artificial Intelligence*, Portland, USA, 2019, pp. 1536–1540.

[247] H. T. Nguyen, M. Garratt, L. T. Bui, and H. Abbass, “Apprenticeship learning for continuous state spaces and actions in a swarm-guidance shepherding task,” in *Proc. IEEE Symp. Series on Computational Intelligence*, Xiamen, China, 2019, pp. 102–109.

[248] H. T. Nguyen, M. Garratt, L. T. Bui, and H. Abbass, “Apprenticeship bootstrapping: Inverse reinforcement learning in a multi-skill UAV-UGV coordination task,” in *Proc. 17th Int. Conf. Autonomous Agents and MultiAgent Systems*, Stockholm, Sweden, 2018, pp. 2204–2206.

[249] X.-l. Chen, L. Cao, Z.-X. Xu, J. Lai, and C.-X. Li, “A study of continuous maximum entropy deep inverse reinforcement learning,” *Math. Probl. Eng.*, vol. 2019, p. 4834516, Apr. 2019.

[250] A. J. Snoswell, S. P. N. Singh, and N. Ye, “Revisiting maximum entropy inverse reinforcement learning: New perspectives and algorithms,” in *Proc. IEEE Symp. Series on Computational Intelligence*, Canberra, Australia, 2020, pp. 241–249.

[251] L. Song, D. Li, X. Wang, and X. Xu, “Adaboost maximum entropy deep inverse reinforcement learning with truncated gradient,” *Inf. Sci.*, vol. 602, pp. 328–350, Jul. 2022. doi: 10.1016/j.ins.2022.04.017

[252] Z. Wu, L. Sun, W. Zhan, C. Yang, and M. Tomizuka, “Efficient sampling-based maximum entropy inverse reinforcement learning with application to autonomous driving,” *IEEE Robot. Autom. Lett.*, vol. 5, no. 4, pp. 5355–5362, Oct. 2020. doi: 10.1109/LRA.2020.3005126

[253] Z. Zhou, M. Bloem, and N. Bambos, “Infinite time horizon maximum causal entropy inverse reinforcement learning,” *IEEE Trans. Autom. Control*, vol. 63, no. 9, pp. 2787–2802, Sept. 2018. doi: 10.1109/TAC.2017.2775960

[254] C. Finn, S. Levine, and P. Abbeel, “Guided cost learning: Deep inverse optimal control via policy optimization,” in *Proc. 33rd Int. Conf. Machine Learning*, New York, USA, 2016, pp. 49–58.

[255] C. Finn, X. Y. Tan, Y. Duan, T. Darrell, S. Levine, and P. Abbeel, “Deep spatial autoencoders for visuomotor learning,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Stockholm, Sweden, 201 pp. 512–519.

[256] T. Zhang, Y. Liu, M. Hwang, K.-S. Hwang, C. Y. Ma, and J. Cheng, “An end-to-end inverse reinforcement learning by a boosting approach with relative entropy,” *Inf. Sci.*, vol. 520, pp. 1–14, May 2020. doi: 10.1016/j.ins.2020.01.023

[257] G. Zuo, K. Chen, J. Lu, and X. Huang, “Deterministic generative adversarial imitation learning,” *Neurocomputing*, vol. 388, pp. 60–69, May 2020. doi: 10.1016/j.neucom.2020.01.016

[258] J. Ho and S. Ermon, “Generative adversarial imitation learning,” in *Proc. 30th Int. Conf. Neural Information Processing Systems*, Barcelona, Spain, 2016, pp. 4572–4580.

[259] G. Zuo, Q. Zhao, S. Huang, J. Li, and D. Gong, “Adversarial imitation learning with mixed demonstrations from multiple demonstrators,” *Neurocomputing*, vol. 457, pp. 365–376, Oct. 2021. doi: 10.1016/j.neucom.2021.06.053

[260] H. Xu, X. Zhan, H. Yin, and H. Qin, “Discriminator-weighted offline imitation learning from suboptimal demonstrations,” in *Proc. 39th Int. Conf. Machine Learning*, Baltimore, USA, 2022, pp 24725–24742.

[261] T. Xu, Z. Li, and Y. Yu, “Error bounds of imitating policies and environments for reinforcement learning,” *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 44, no. 10, pp. 6968–6980, Oct. 2022. doi: 10.1109/TPAMI.2021.3096966

[262] M. Taylor, S. Bashkirov, J. F. Rico, I. Toriyama, N. Miyada, H. Yanagisawa, and K. Ishizuka, “Learning bipedal robot locomotion from human movement,” in *Proc. IEEE Int. Conf. Robotics ar Automation*, Xi’an, China, 2021, pp. 2797–2803.

[263] R. Batke, F. Yu, J. Dao, J. Hurst, R. L. Hatton, A. Fern, and K. Green, “Optimizing bipedal maneuvers of single rigid-body models for reinforcement learning,” in *Proc. IEEE-RAS 21st Int. Conf. Humanoid Robots*, Ginowan, Japan, 2022, pp. 714–721.

[264] V. Krishnamurthy and G. Yin, “Langevin dynamics for adaptive inverse reinforcement learning of stochastic gradient algorithms,” *J. Mach. Learn. Res.*, vol. 22, pp. 1–49, Apr. 2021.

[265] S. Krishnan, A. Garg, R. Liaw, B. Thananjeyan, L. Miller, F. T. Pokorny, and K. Goldberg, "SWIR
A sequential windowed inverse reinforcement learning algorithm for robot tasks with delayed rewards," *Int. J. Robot. Res.*, vol. 38, no. 2-3, pp. 126–145, Mar. 2019. doi: 10.1177/0278364918784350

[266] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing-from humans to humanoids," *IEEE Trans. Robot.*, vol. 26, no. 1, pp. 1–20, Feb. 2010. doi: 10.1109/TRO.2009.2033627

[267] Y. H. Jung, B. Park, J. U. Kim, and T.-I. Kim, "Bioinspired electronics for artificial sensory systems," *Adv. Mater.*, vol. 31, no. 34, p. 1803637, Aug. 2019. doi: 10.1002/adma.201803637

[268] M. Soni, M. Bhattacharjee, M. Ntagios, and R. Dahiya, "Printed temperature sensor based on PEDOT: PSS-graphene oxide composite," *IEEE Sensors J.*, vol. 20, no. 14, pp. 7525–7531, Jul. 2020. doi: 10.1109/JSEN.2020.2969667

[269] J. Yan, Y. Ma, X. Li, C. Zhang, M. Cao, W. Chen, S. Luo, M. Zhu, and Y. Gao, "Flexible and high
sensitivity piezoresistive sensor based on MXene composite with wrinkle structure," *Ceram. Int.*, v
46, no. 15, pp. 23592–23598, Oct. 2020. doi: 10.1016/j.ceramint.2020.06.131

[270] S. Chitta, E. G. Jones, M. Ciocarlie, and K. Hsiao, "Mobile manipulation in unstructured environments: Perception, planning, and execution," *IEEE Robot. Autom. Mag.*, vol. 19, no. 2, pp. 58–71, Jun. 2012. doi: 10.1109/MRA.2012.2191995

[271] S. Elliott, M. Valente, and M. Cakmak, "Making objects graspable in confined environments throu
push and pull manipulation with a tool," in *Proc. IEEE Int. Conf. Robotics and Automation*, Stockholm, Sweden, 2016, pp. 4851–4858.

[272] D. Lee and Y. Nakamura, "Mimesis scheme using a monocular vision system on a humanoid robot
in *Proc. IEEE Int. Conf. Robotics and Automation*, Rome, Italy, 2007, pp. 2162–2168.

[273] K. Sabe, M. Fukuchi, J.-S. Gutmann, T. Ohashi, K. Kawamoto, and T. Yoshigahara, "Obstacle avoidance and path planning for humanoid robots using stereo vision," in *Proc. IEEE Int. Conf. Robotics and Automation*, New Orleans, USA, 2004, pp. 592–597.

[274] J. Schulman, Y. Duan, J. Ho, A. Lee, I. Awwal, H. Bradlow, J. Pan, S. Patil, K. Goldberg, and P. Abbeel, "Motion planning with sequential convex optimization and convex collision checking," *In
J. Robot. Res.*, vol. 33, no. 9, pp. 1251–1270, Aug. 2014. doi: 10.1177/0278364914528132

[275] N. Perrin, O. Stasse, L. Baudouin, F. Lamiraux, and E. Yoshida, "Fast humanoid robot collision-fre
footstep planning using swept volume approximations," *IEEE Trans. Robot.*, vol. 28, no. 2, pp. 427
439, Apr. 2012. doi: 10.1109/TRO.2011.2172152

[276] H.-W. Park, A. Ramezani, and J. W. Grizzle, "A finite-state machine for accommodating unexpect
large ground-height variations in bipedal robot walking," *IEEE Trans. Robot.*, vol. 29, no. 2, pp. 33
345, Apr. 2013. doi: 10.1109/TRO.2012.2230992

[277] T. Morita, K. Mase, Y. Hirano, and S. Kajita, "Reciprocal attentive communication in remote meet
with a humanoid robot," in *Proc. 9th Int. Conf. Multimodal Interfaces*, Nagoya Aichi, Japan, 2007, pp. 228–235.

[278] J.-S. Gutmann, M. Fukuchi, and M. Fujita, “A floor and obstacle height map for 3D navigation of a humanoid robot,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Barcelona, Spain, 2005, pp. 1066–1071.

[279] H. Zhang and E. So, “Hybrid resistive tactile sensing,” *IEEE Trans. Syst. Man Cybern. Part B* (*Cybern.*), vol. 32, no. 1, pp. 57–65, Feb. 2002. doi: 10.1109/3477.979960

[280] P. A. Schmidt, E. Maël, and R. P. Würtz, “A sensor for dynamic tactile information with applicatio in human-robot interaction and object exploration,” *Robot. Auton. Syst.*, vol. 54, no. 12, pp. 1005–1014, Dec. 2006. doi: 10.1016/j.robot.2006.05.013

[281] C. H. Lee, C. G. Park, H. S. Lee, J. G. Lee, C. W. Jeon, M. K. Kim, W. Kwon, Y. M. Yoo, J. I. Kir and G. B. Moon, “Development of indoor navigation system for humanoid robot using multi-senso integration,” in *Proc. Nat. Technical Meeting Institute-of-Navigation*, San Diego, USA, 2007, pp. 798–805.

[282] T. Dutta and G. R. Fernie, “Utilization of ultrasound sensors for anti-collision systems of powered wheelchairs,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 1, pp. 24–32, Mar. 2005. doi: 10.1109/TNSRE.2004.842366

[283] F. Abrate, B. Bona, and M. Indri, “Monte Carlo localization of mini-rovers with low-cost IR senso in *Proc. IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics*, Zurich, Switzerland, 2007, pp. 768–773.

[284] H. H. Cheng, B. D. Shaw, J. Palen, J. E. Larson, X. Hu, and K. Van Katwyk, “A real-time laser-bas detection system for measurement of delineations of moving vehicles,” *IEEE/ASME Trans. Mechatron.*, vol. 6, no. 2, pp. 170–187, Jun. 2001. doi: 10.1109/3516.928732

[285] O. Duran, K. Althoefer, and L. D. Seneviratne, “Pipe inspection using a laser-based transducer and automated analysis techniques,” *IEEE/ASME Trans. Mechatron.*, vol. 8, no. 3, pp. 401–409, Sept. 2003. doi: 10.1109/TMECH.2003.816809

[286] D. Goger, N. Gorges, and H. Worn, “Tactile sensing for an anthropomorphic robotic hand: Hardwa and signal processing,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Kobe, Japan, 2009, pp. 2972–2978.

[287] N. F. Lepora, C. Ford, A. Stinchcombe, A. Brown, J. Lloyd, M. G. Catalano, M. Bianchi, and B. Ward-Cherrier, “Towards integrated tactile sensorimotor control in anthropomorphic soft robotic hands,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Xi’an, China, 2021, pp. 1622–1628.

[288] T.-H. Chang, Y. Tian, C. Li, X. Gu, K. Li, H. Yang, P. Sanghani, C. M. Lim, H. Ren, and P.-Y. Ch “Stretchable graphene pressure sensors with Shar-Pei-like hierarchical wrinkles for collision-aware surgical robotics,” *ACS Appl. Mater. Interfaces*, vol. 11, no. 10, pp. 10226–10236, Feb. 2019. doi: 10.1021/acsami.9b00166

[289] M. Prats, P. J. Sanz, and A. P. del Pobil, “Vision-tactile-force integration and robot physical interaction,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Kobe, Japan, 2009, pp. 2118–2123

[290] Q. Li, R. Haschke, and H. Ritter, “A visuo-tactile control framework for manipulation and exploration of unknown objects,” in *Proc. IEEE-RAS 15th Int. Conf. Humanoid Robots*, Seoul, Sou Korea, 2015, pp. 610–615.

[291] Y. Yoon, W.-R. Ko, M. Jang, J. Lee, J. Kim, and G. Lee, "Robots learn social skills: End-to-end learning of Co-speech gesture generation for humanoid robots," in *Proc. Int. Conf. Robotics and Automation*, Montreal, Canada, 2019, pp. 4303–4309.

[292] H. Modares, I. Ranatunga, F. L. Lewis, and D. O. Popa, "Optimized assistive human-robot interact using reinforcement learning," *IEEE Trans. Cybern.*, vol. 46, no. 3, pp. 655–667, Mar. 2016. doi: 10.1109/TCYB.2015.2412554

[293] A. L. Shoushtari, P. Dario, and S. Mazzoleni, "A review on the evolvement trend of robotic interaction control," *Ind. Robot*, vol. 43, no. 5, pp. 535–551, Aug. 2016. doi: 10.1108/IR-02-2016-0073

[294] H. Huang, C. Yang, and C. L. P. Chen, "Optimal robot-environment interaction under broad fuzzy neural adaptive control," *IEEE Trans. Cybern.*, vol. 51, no. 7, pp. 3824–3835, Jul. 2021. doi: 10.1109/TCYB.2020.2998984

[295] J. Baltes, K.-Y. Tu, S. Sadeghnejad, and J. Anderson, "HuroCup: Competition for multi-event humanoid robot athletes," *Knowl. Eng. Rev.*, vol. 32, p. e1, 2017. doi: 10.1017/S026988891600011

[296] E. Krotkov, D. Hackett, L. Jackel, M. Perschbacher, J. Pippine, J. Strauss, G. Pratt, and C. Orlowsk "The DARPA robotics challenge finals: Results and perspectives," *J. Field Robot.*, vol. 34, no. 2, p 229–240, Mar. 2017. doi: 10.1002/rob.21683

[297] J. Anderson, J. Baltes, and C. T. Cheng, "Robotics competitions as benchmarks for AI research," *Knowl. Eng. Rev.*, vol. 26, no. 1, pp. 11–17, Feb. 2011. doi: 10.1017/S02698889100003

[298] T. B. Martin, R. O. Ambrose, M. A. Diftler, R. Platt, and M. J. Butzer, "Tactile gloves for autonomous grasping with the NASA/DARPA robonaut," in *Proc. IEEE Int. Conf. Robotics and Automation*, New Orleans, USA, 2004, pp. 1713-1718.

[299] C. G. Atkeson, B. P. W. Babu, N. Banerjee, D. Berenson, C. P. Bove, X. Cui, M. DeDonato, R. Du S. Feng, P. Franklin, M. Gennert, J. P. Graff, P. He, A. Jaeger, J. Kim, K. Knoedler, L. Li, C. Liu, Long, T. Padir, F. Polido, G. G. Tighe, and X. Xinjilefu, "No falls, no resets: Reliable humanoid behavior in the DARPA robotics challenge," in *Proc. IEEE-RAS 15th Int. Conf. Humanoid Robots*, Seoul, South Korea, 2015, pp. 623–630.

[300] M. DeDonato, V. Dimitrov, R. Du, R. Giovacchini, K. Knoedler, X. Long, F. Polido, M. A. Genne T. Padır, S. Feng, H. Moriguchi, E. Whitman, X. Xinjilefu, and C. G. Atkeson, "Human-in-the-loo control of a humanoid robot for disaster response: A report from the DARPA robotics challenge trials," *J. Field Robot.*, vol. 32, no. 2, pp. 275–292, Mar. 2015. doi: 10.1002/rob.21567

[301] R. Latikka, T. Turja, and A. Oksanen, "Self-efficacy and acceptance of robots," *Comput. Hum. Behav.*, vol. 93, pp. 157–163, Apr. 2019. doi: 10.1016/j.chb.2018.12.017

[302] M. Andtfolk, L. Nyholm, H. Eide, and L. Fagerstrom, "Humanoid robots in the care of older persor A scoping review," *Assistive Technol.*, vol. 34, no. 5, pp. 518–526, Sept. 2022. doi: 10.1080/10400435.2021.1880493

[303] A. Fan, L. Wu, L. Miao, and A. S. Manila, "When does technology anthropomorphism help allevia customer dissatisfaction after a service failure? – The moderating role of consumer technology self

efficacy and interdependent self-construal," *J. Hospitality Mark. Manage.*, vol. 29, no. 3, pp. 269–290, Apr. 2020. doi: 10.1080/19368623.2019.1639095

[304] I. Papadopoulos, C. Koulouglioti, R. Lazzarino, and S. Ali, "Enablers and barriers to the implementation of socially assistive humanoid robots in health and social care: A systematic review," *BMJ Open*, vol. 10, no. 1, p. e033096, 2020. doi: 10.1136/bmjopen-2019-033096

[305] M. Mende, M. L. Scott, J. van Doorn, D. Grewal, and I. Shanks, "Service robots rising: How humanoid robots influence service experiences and elicit compensatory consumer responses," *J. Mark. Res.*, vol. 56, no. 4, pp. 535–556, Aug. 2019. doi: 10.1177/0022243718822827

[306] S. Choi, A. S. Mattila, and L. E. Bolton, "To err is human(-oid): How do consumers react to robot service failure and recovery?" *J. Ser. Res.*, vol. 24, no. 3, pp. 354–371, Aug. 2021. doi: 10.1177/1094670520978798

[307] J. Hemminahaus and S. Kopp, "Towards adaptive social behavior generation for assistive robots using reinforcement learning," in *Proc. 12th ACM/IEEE Int. Conf. Human-Robot Interaction*, Vien Austria, 2017, pp. 332–340.

[308] M. M. E. van Pinxteren, R. W. H. Wetzels, J. Rüger, M. Pluymaekers, and M. Wetzels, "Trust in humanoid robots: Implications for services marketing," *J. Ser. Mark.*, vol. 33, no. 4, pp. 507–518, J 2019. doi: 10.1108/JSM-01-2018-0045

[309] D. H. Zhu and Y. P. Chang, "Robot with humanoid hands cooks food better? Effect of robotic chef anthropomorphism on food quality prediction," *Int. J. Contemp. Hospitality Manage.*, vol. 32, no. 3 pp. 1367–1383, Apr. 2020. doi: 10.1108/IJCHM-10-2019-0904

[310] V. Yoganathan, V.-S. Osburg, W. H. Kunz, and W. Toporowski, "Check-in at the Robo-desk: Effe of automated social presence on social cognition and service implications," *Tourism Manage.*, vol. 85, p. 104309, Aug. 2021. doi: 10.1016/j.tourman.2021.104309

[311] A. Asghar, A. Patra, and K. S. Ravi, "The potential scope of a humanoid robot in anatomy educatio A review of a unique proposal," *Surg. Radiol. Anat.*, vol. 44, no. 10, pp. 1309–1317, Sept. 2022. doi: 10.1007/s00276-022-03020-8

[312] L. Chen, P. Chen, and Z. Lin, "Artificial intelligence in education: A review," *IEEE Access*, vol. 8, pp. 75264–75278, Apr. 2020. doi: 10.1109/ACCESS.2020.2988510

[313] A. Dante, C. La Cerra, V. Masotta, V. Caponnetto, L. Bertocchi, A. Marcotullio, F. Ferraiuolo, C. I Alfes, and C. Petrucci, "The use of robotics to enhance learning in nursing education: A scoping review," in *Methodologies and Intelligent Systems for Technology Enhanced Learning, 11th International Conference*, F. De la Prieta, R. Gennari, M. Temperini, T. Di Mascio, P. Vittorini, Z. Kubincova, E. Popescu, D. R. Carneiro, L. Lancia, and A. Addone, Eds. Cham, Germany: Springer 2022, pp. 217–226.

[314] Y. Lau, D. G. H. Chee, X. P. Chow, S. H. Wong, L. J. Cheng, and S. T. Lau, "Humanoid robot-assisted interventions among children with diabetes: A systematic scoping review," *Int. J. Nurs. Stud.*, vol. 111, p. 103749, Nov. 2020. doi: 10.1016/j.ijnurstu.2020.103749

[315] J. Dawe, C. Sutherland, A. Barco, and E. Broadbent, “Can social robots help children in healthcare contexts? A scoping review,” *BMJ Paediatr. Open*, vol. 3, no. 1, p. e000371, Jan. 2019. doi: 10.1136/bmjpo-2018-000371

[316] G. Zambella, R. Schuller, G. Mesesan, A. Bicchi, C. Ott, and J. Lee, “Agile and dynamic standing-control for humanoids using 3D divergent component of motion in multi-contact scenario,” *IEEE Robot. Autom. Lett.*, vol. 8, no. 9, pp. 5624–5631, Sept. 2023. doi: 10.1109/LRA.2023.3297060

[317] P. Sun, Y. Gu, H. Mao, Z. Chen, and Y. Li, “Research on walking gait planning and simulation of a novel hybrid biped robot,” *Biomimetics*, vol. 8, no. 2, p. 258, Jun. 2023. doi: 10.3390/biomimetics8020258

[318] Y. Lee and T.-W. Lee, “Organic synapses for neuromorphic electronics: From brain-inspired computing to sensorimotor nervetronics,” *Acc. Chem. Res.*, vol. 52, no. 4, pp. 964–974, Mar. 2019. doi: 10.1021/acs.accounts.8b00553

[319] Y. Chae, J. Jeong, and S. Jo, “Toward brain-actuated humanoid robots: Asynchronous direct contro using an EEG-based BCI,” *IEEE Trans. Robot.*, vol. 28, no. 5, pp. 1131–1144, Oct. 2012. doi: 10.1109/TRO.2012.2201310

[320] R. Ma, S.-Y. Chou, Y. Xie, and Q. Pei, “Morphological/nanostructural control toward intrinsically stretchable organic electronics,” *Chem. Soc. Rev.*, vol. 48, no. 6, pp. 1741–1786, Jan. 2019. doi: 10.1039/C8CS00834E

[321] B. Wang, Z. Wang, Y. Song, W. Zong, L. Zhang, K. Ji, P. Manoonpong, and Z. Dai, “A neural coordination strategy for attachment and detachment of a climbing robot inspired by gecko locomotion,” *Cyborg Bionic Syst.*, vol. 4, p. 8, Feb. 2023. doi: 10.34133/cbsystems.0008

[322] J. A. Reggia, G. E. Katz, and G. P. Davis, “Humanoid cognitive robots that learn by imitating: Implications for consciousness studies,” *Front. Robot. AI*, vol. 5, p. 1, Jan. 2018. doi: 10.3389/frobt.2018.00001

[323] G. Feng, J. Jiang, Y. Zhao, S. Wang, B. Liu, K. Yin, D. Niu, X. Li, Y. Chen, H. Duan, J. Yang, J. H Y. Gao, and Q. Wan, “A sub-10 nm vertical organic/inorganic hybrid transistor for pain-perceptual and sensitization-regulated nociceptor emulation,” *Adv. Mater.*, vol. 32, no. 6, p. 1906171, Feb. 2020. doi: 10.1002/adma.201906171

[324] S. Chun, W. Son, H. Kim, S. K. Lim, C. Pang, and C. Choi, “Self-powered pressure- and vibration-sensitive tactile sensors for learning technique-based neural finger skin,” *Nano Lett.*, vol. 19, no. 5, pp. 3305–3312, Apr. 2019. doi: 10.1021/acs.nanolett.9b00922

[325] R. Dahiya, D. Akinwande, and J. S. Chang, “Flexible electronic skin: From humanoids to humans[Scanning the Issue],” *Proc. IEEE*, vol. 107, no. 10, pp. 2011–2015, Oct. 2019. doi: 10.1109/JPROC.2019.2941665

[326] R. Dahiya, “E-skin: From humanoids to humans [Point of View],” *Proc. IEEE*, vol. 107, no. 2, pp. 247–252, Feb. 2019. doi: 10.1109/JPROC.2018.2890729

[327] H. Tang, S. Zhang, Y. Tian, T. Kang, C. Zhou, S. Yang, Y. Liu, X. Liu, Q. Chen, H. Xiao, W. Che and J. Zang, “Bioinspired soft elastic metamaterials for reconstruction of natural hearing,” *Adv. Sci* vol. 10, no. 20, p. 2207273, Jul. 2023. doi: 10.1002/advs.202207273

[328] W. Li, H. Liang, Y. Ao, B. Tang, J. Li, N. Li, J. Wang, and Y. Du, "Biophysical cues of bone marrow-inspired scaffolds regulate hematopoiesis of hematopoietic stem and progenitor cells," *Biomaterials*, vol. 298, p. 122111, Jul. 2023. doi: 10.1016/j.biomaterials.2023.122111

[329] Z. Cao, Y. Yang, Y. Zheng, W. Wu, F. Xu, R. Wang, and J. Sun, "Highly flexible and sensitive temperature sensors based on $Ti_3C_2T_x$ (MXene) for electronic skin," *J. Mater. Chem. A*, vol. 7, no. 4 pp. 25314–25323, Oct. 2019. doi: 10.1039/C9TA09225K

[330] X. Ling, M. I. Osotsi, W. Zhang, Y. Wu, Q. Jin, and D. Zhang, "Bioinspired materials: From distin dimensional architecture to thermal regulation properties," *J. Bionic Eng.*, vol. 20, no. 3, pp. 873–8 May 2023. doi: 10.1007/s42235-022-00314-w

[331] K. Wan, X. Gou, and Z. Guo, "Bio-inspired fog harvesting materials: Basic research and bionic potential applications," *J. Bionic Eng.*, vol. 18, no. 3, pp. 501–533, Jun. 2021. doi: 10.1007/s42235 021-0040-0

[332] H. Peng, F. Li, J. Liu, and Z. Ju, "A symplectic instantaneous optimal control for robot trajectory tracking with differential-algebraic equation models," *IEEE Trans. Ind. Electron.*, vol. 67, no. 5, pp 3819–3829, May 2020. doi: 10.1109/TIE.2019.2916390

[333] B. Chen, X. Liu, and S. Tong, "Adaptive fuzzy output tracking control of MIMO nonlinear uncerta systems," *IEEE Trans. Fuzzy Syst.*, vol. 15, no. 2, pp. 287–300, Apr. 2007. doi: 10.1109/TFUZZ.2006.880008

[334] Y. Hu, X. Wu, P. Geng, and Z. Li, "Evolution strategies learning with variable impedance control f grasping under uncertainty," *IEEE Trans. Ind. Electron.*, vol. 66, no. 10, pp. 7788–7799, Oct. 2019. doi: 10.1109/TIE.2018.2884240

[335] F. Ficuciello, A. Migliozzi, G. Laudante, P. Falco, and B. Siciliano, "Vision-based grasp learning o an anthropomorphic hand-arm system in a synergy-based control framework," *Sci. Robot.*, vol. 4, n 26, p. eaao4900, Jan. 2019. doi: 10.1126/scirobotics.aao4900

[336] S. Saeedvand, H. S. Aghdasi, and J. Baltes, "Robust multi-objective multi-humanoid robots task allocation based on novel hybrid metaheuristic algorithm," *Appl. Intell.*, vol. 49, no. 12, pp. 4097–4127, Dec. 2019. doi: 10.1007/s10489-019-01475-8

[337] K. Bouyarmane, K. Chappellet, J. Vaillant, and A. Kheddar, "Quadratic programming for multirob and task-space force control," *IEEE Trans. Robot.*, vol. 35, no. 1, pp. 64–77, Feb. 2019. doi: 10.1109/TRO.2018.2876782

[338] R. Saitake and S. Arai, "Parameter estimation of multi-objective reinforcement learning to reach arbitrary Pareto solution," in *Proc. IEEE Int. Conf. Agents*, Matsue, Japan, 2016, pp. 110–111.

[339] W. Buckel and R. K. Thauer, "Flavin-based electron bifurcation, a new mechanism of biological energy coupling," *Chem. Rev.*, vol. 118, no. 7, pp. 3862–3886, Mar. 2018. doi: 10.1021/acs.chemrev.7b00707

[340] F. Arvin, K. Samsudin, and A. R. Ramli, "Development of IR-based short-range communication techniques for swarm robot applications," *Adv. Electr. Comput. Eng.*, vol. 10, no. 4, pp. 61–68, No 2010. doi: 10.4316/aece.2010.04010

[341] G. A. LePage, "Biological energy transformations during shock as shown by tissue analyses," *Am. Physiol.*, vol. 146, no. 2, pp. 267–281, May 1946. doi: 10.1152/ajplegacy.1946.146.2.267

[342] K. R. Foster, "Thermal and nonthermal mechanisms of interaction of radio-frequency energy with biological systems," *IEEE Trans. Plasma Sci.*, vol. 28, no. 1, pp. 15–23, Feb. 2000. doi: 10.1109/27.842819

[343] D. Beljonne, C. Curutchet, G. D. Scholes, and R. J. Silbey, "Beyond förster resonance energy trans in biological and nanoscale systems," *J. Phys. Chem. B*, vol. 113, no. 19, pp. 6583–6599, Mar. 2009. doi: 10.1021/jp900708f

[344] S. J. McMahon, W. B. Hyland, M. F. Muir, J. A. Coulter, S. Jain, K. T. Butterworth, G. Schettino, R. Dickson, A. R. Hounsell, J. M. O'Sullivan, K. M. Prise, D. G. Hirst, and F. J. Currell, "Biologic consequences of nanoscale energy deposition near irradiated heavy atom nanoparticles," *Sci. Rep.*, vol. 1, no. 1, p. 18, Jun. 2011. doi: 10.1038/srep00018

[345] H.-Q. Peng, L.-Y. Niu, Y.-Z. Chen, L.-Z. Wu, C.-H. Tung, and Q.-Z. Yang, "Biological applicatio of supramolecular assemblies designed for excitation energy transfer," *Chem. Rev.*, vol. 115, no. 15 pp. 7502–7542, Jun. 2015. doi: 10.1021/cr5007057

[346] H. Zhu, W. Luo, P. N. Ciesielski, Z. Fang, J. Y. Zhu, G. Henriksson, M. E. Himmel, and L. Hu, "Wood-derived materials for green electronics, biological devices, and energy applications," *Chem Rev.*, vol. 116, no. 16, pp. 9305–9374, Jul. 2016. doi: 10.1021/acs.chemrev.6b00225

[347] E. Uslu, F. Çakmak, N. Altuntaş, S. Marangoz, M. F. Amasyalı, and S. Yavuz, "An architecture fo multi-robot localization and mapping in the gazebo/robot operating system simulation environment," *Simulation*, vol. 93, no. 9, pp. 771–780, Sept. 2017. doi: 10.1177/003754971771009

[348] S. A. Prieto, A. Adán, A. S. Vázquez, and B. Quintana, "Passing through open/closed doors: A solution for 3D scanning robots," *Sensors*, vol. 19, no. 21, p. 4740, Oct. 2019. doi: 10.3390/s19214740

[349] C. X. Er Shamaine, Y. Qiao, J. Henry, K. McNevin, and N. Murray, "RoSTAR: ROS-based telerobotic control via augmented reality," in *Proc. IEEE 22nd Int. Workshop on Multimedia Signa Processing*, Tampere, Finland, 2020, pp. 1–6.

[350] H. Kato, D. Hirano, S. Mitani, T. Saito, and S. Kawaguchi, "ROS and cFS system (RACS): Easing space robotic development," in *Proc. IEEE Aerospace Conf.*, Big Sky, USA, 2021, pp. 1-8.

[351] D. Whitney, E. Rosen, D. Ullman, E. Phillips, and S. Tellex, "ROS reality: A virtual reality framework using consumer-grade hardware for ROS-enabled robots," in *Proc. IEEE/RSJ Int. Conf Intelligent Robots and Systems*, Madrid, Spain, 2018, pp. 5018–5025.

[352] J. Orr and A. Dutta, "Multi-agent deep reinforcement learning for multi-robot applications: A survey," *Sensors*, vol. 23, no. 7, p. 3625, Mar. 2023. doi: 10.3390/s23073625

[353] T. Fong, C. Thorpe, and C. Baur, "Multi-robot remote driving with collaborative control," *IEEE Trans. Ind. Electron.*, vol. 50, no. 4, pp. 699–704, Aug. 2003. doi: 10.1109/TIE.2003.814768

[354] L. Vig and J. A. Adams, "Multi-robot coalition formation," *IEEE Trans. Robot.*, vol. 22, no. 4, pp. 637–649, Aug. 2006. doi: 10.1109/TRO.2006.878948

[355] Y. Cai, Z. Tang, Y. Ding, and B. Qian, "Theory and application of multi-robot service-oriented architecture," *IEEE/CAA J. Autom. Sinica*, vol. 3, no. 1, pp. 15–25, Jan. 2016. doi: 10.1109/JAS.2016.7373758

[356] S. Trigui, O. Cheikhrouhou, A. Koubaa, U. Baroudi, and H. Youssef, "FL-MTSP: A fuzzy logic approach to solve the multi-objective multiple traveling salesman problem for multi-robot systems," *Soft Comput.*, vol. 21, no. 24, pp. 7351–7362, Dec. 2017. doi: 10.1007/s00500-016-2279

[357] M. Appel, D. Izydorczyk, S. Weber, M. Mara, and T. Lischetzke, "The uncanny of mind in a machine: Humanoid robots as tools, agents, and experiencers," *Comput. Hum. Behav.*, vol. 102, pp. 274–286, Jan. 2020. doi: 10.1016/j.chb.2019.07.031

[358] S. Naneva, M. S. Gou, T. L. Webb, and T. J. Prescott, "A systematic review of attitudes, anxiety, acceptance, and trust towards social robots," *Int. J. Soc. Robot.*, vol. 12, no. 6, pp. 1179–1201, Dec 2020. doi: 10.1007/s12369-020-00659-4

[359] S. Saunderson and G. Nejat, "Hybrid hierarchical learning for adaptive persuasion in human-robot interaction," *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 5520–5527, Apr. 2022. doi: 10.1109/LRA.2022.3140813

[360] Z. Zeng, P.-J. Chen, and A. A. Lew, "From high-touch to high-tech: COVID-19 drives robotics adoption," *Tourism Geogr.*, vol. 22, no. 3, pp. 724–734, May 2020. doi: 10.1080/14616688.2020.1762118

[361] A. Edwards, C. Edwards, D. Westerman, and P. R. Spence, "Initial expectations, interactions, and beyond with social robots," *Comput. Hum. Behav.*, vol. 90, pp. 308–314, Jan. 2019. doi: 10.1016/j.chb.2018.08.042

[362] Y. Cha and S. Hong, "Energy harvesting from walking motion of a humanoid robot using a piezoelectric composite," *Smart Mater. Struct.*, vol. 25, no. 10, p. 10LT01, Sept. 2016. doi: 10.1088/0964-1726/25/10/10LT01

[363] W.-Y. Li, H. Nabae, G. Endo, and K. Suzumori, "New soft robot hand configuration with combine biotensegrity and thin artificial muscle," *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 4345–4351, Ju 2020. doi: 10.1109/LRA.2020.2983668

[364] M. Kawai, M. Nie, H. Oda, Y. Morimoto, and S. Takeuchi, "Living skin on a robot," *Matter*, vol. 5 no. 7, pp. 2190–2208, Jul. 2022. doi: 10.1016/j.matt.2022.05.019

[365] J. Long, J. Li, Y. Lu, C. Zhou, G. Lu, and Y. Feng, "Shape-changing robotic mannequin shoulder with bio-inspired layered structure," *IEEE Robot. Autom. Lett.*, vol. 8, no. 8, pp. 5172–5179, Aug. 2023. doi: 10.1109/LRA.2023.3293753

[366] X. Zhang, N. Sun, G. Liu, T. Yang, and Y. Fang, "Hysteresis compensation-based intelligent contr for pneumatic artificial muscle-driven humanoid robot manipulators with experiments verification," *IEEE Trans. Autom. Sci. Eng.*, 2023. DOI: 10.1109/TASE.2023.3263535

[367] P. Mittendorfer and G. Cheng, "Humanoid multimodal tactile-sensing modules," *IEEE Trans. Rob* vol. 27, no. 3, pp. 401–410, Jun. 2011. doi: 10.1109/TRO.2011.2106330

[368] M. Fridin, "Kindergarten social assistive robot: First meeting and ethical issues," *Comput. Hum. Behav.*, vol. 30, pp. 262–272, Jan. 2014. doi: 10.1016/j.chb.2013.09.005

[369] D. Vanderelst and A. Winfield, “An architecture for ethical robots inspired by the simulation theor of cognition,” *Cognit. Syst. Res.*, vol. 48, pp. 56–66, May 2018. doi: 10.1016/j.cogsys.2017.04.002

[370] J. Fox and A. Gambino, “Relationship development with humanoid social robots: Applying interpersonal theories to human-robot interaction,” *Cyberpsychol.,Behav.,Soc. Netw.*, vol. 24, no. 5 pp. 294–299, May 2021. doi: 10.1089/cyber.2020.0181

- ## Related Articles

[1] Meng Zhou, Zihao Wang, Jing Wang, Zhengcai Cao. Multi-Robot Collaborative Hunting in Cluttere Environments With Obstacle-Avoiding Voronoi Cells[J]. IEEE/CAA Journal of Automatica Sinica, 2024, 11(7): 1643-1655. doi: 10.1109/JAS.2023.124041

[2] Qinchen Yang, Fukai Zhang, Cong Wang. Deterministic Learning-Based Neural PID Control for Nonlinear Robotic Systems[J]. IEEE/CAA Journal of Automatica Sinica, 2024, 11(5): 1227-1238. doi: 10.1109/JAS.2024.124224

[3] Shengnan Gao, Zhouhua Peng, Haoliang Wang, Lu Liu, Dan Wang. Long Duration Coverage Contr of Multiple Robotic Surface Vehicles Under Battery Energy Constraints[J]. IEEE/CAA Journal of Automatica Sinica, 2024, 11(7): 1695-1698. doi: 10.1109/JAS.2023.123438

[4] Yunjun Zheng, Jinchuan Zheng, Ke Shao, Han Zhao, Hao Xie, Hai Wang. Adaptive Trajectory Tracking Control for Nonholonomic Wheeled Mobile Robots: A Barrier Function Sliding Mode Approach[J]. IEEE/CAA Journal of Automatica Sinica, 2024, 11(4): 1007-1021. doi: 10.1109/JAS.2023.124002

[5] Qiming Liu, Xinru Cui, Zhe Liu, Hesheng Wang. Cognitive Navigation for Intelligent Mobile Robo A Learning-Based Approach With Topological Memory Configuration[J]. IEEE/CAA Journal of Automatica Sinica, 2024, 11(9): 1933-1943. doi: 10.1109/JAS.2024.124332

[6] Dezhen Xiong, Daohui Zhang, Yaqi Chu, Yiwen Zhao, Xingang Zhao. Intuitive Human-Robot-Environment Interaction With EMG Signals: A Review[J]. IEEE/CAA Journal of Automatica Sinica 2024, 11(5): 1075-1091. doi: 10.1109/JAS.2024.124329

[7] Tianyu Wu, Shizhu He, Jingping Liu, Siqi Sun, Kang Liu, Qing-Long Han, Yang Tang. A Brief Overview of ChatGPT: The History, Status Quo and Potential Future Development[J]. IEEE/CAA Journal of Automatica Sinica, 2023, 10(5): 1122-1136. doi: 10.1109/JAS.2023.123618

[8] Yongliang Yang, Zihao Ding, Rui Wang, Hamidreza Modares, Donald C. Wunsch. Data-Driven Human-Robot Interaction Without Velocity Measurement Using Off-Policy Reinforcement Learning[J]. IEEE/CAA Journal of Automatica Sinica, 2022, 9(1): 47-63. doi: 10.1109/JAS.2021.1004258

[9] Bixiao Wu, Junpei Zhong, Chenguang Yang. A Visual-Based Gesture Prediction Framework Applie in Social Robots[J]. IEEE/CAA Journal of Automatica Sinica, 2022, 9(3): 510-519. doi: 10.1109/JAS.2021.1004243

[10] Qiyue Wang, Wenhua Jiao, Peng Wang, YuMing Zhang. Digital Twin for Human-Robot Interactive Welding and Welder Behavior Analysis[J]. IEEE/CAA Journal of Automatica Sinica, 2021, 8(2): 33 343. doi: 10.1109/JAS.2020.1003518

[11] Yuchuang Tong, Jinguo Liu. Review of Research and Development of Supernumerary Robotic Limbs[J]. IEEE/CAA Journal of Automatica Sinica, 2021, 8(5): 929-952. doi: 10.1109/JAS.2021.1003961

[12] Zhihao Shen, Armagan Elibol, Nak Young Chong. Understanding Nonverbal Communication Cues Human Personality Traits in Human-Robot Interaction[J]. IEEE/CAA Journal of Automatica Sinica, 2020, 7(6): 1465-1477. doi: 10.1109/JAS.2020.1003201

[13] Zhijun Li, C. L. Philip Chen, Wei He. Guest Editorial forSpecial Issue on Human-centered Intellige Robots:Issues and Challenges[J]. IEEE/CAA Journal of Automatica Sinica, 2017, 4(4): 599-601. doi: 10.1109/JAS.2017.7510601

[14] Ali Safavi, Mehrdad H. Zadeh. Teaching the User By Learning From the User:Personalizing Movement Control in Physical Human-robot Interaction[J]. IEEE/CAA Journal of Automatica Sinic 2017, 4(4): 704-713. doi: 10.1109/JAS.2017.7510634

[15] Zhentao Liu, Min Wu, Weihua Cao, Luefeng Chen, Jianping Xu, Ri Zhang, Mengtian Zhou, Junwei Mao. A Facial Expression Emotion Recognition Based Human-robot Interaction System[J]. IEEE/CAA Journal of Automatica Sinica, 2017, 4(4): 668-676. doi: 10.1109/JAS.2017.7510622

[16] Ningbo Yu, Wulin Zou, Wen Tan, Zhuo Yang. Augmented Virtual Stiffness Rendering of a Cable-driven SEA for Human-Robot Interaction[J]. IEEE/CAA Journal of Automatica Sinica, 2017, 4(4): 714-723. doi: 10.1109/JAS.2017.7510637

[17] Dongcai Lu, Xiaoping Chen. Interpreting and Extracting Open Knowledge for Human-Robot Interaction[J]. IEEE/CAA Journal of Automatica Sinica, 2017, 4(4): 686-695. doi: 10.1109/JAS.2017.7510628

[18] Wei He, Zhijun Li, C. L. Philip Chen. A Survey of Human-centered Intelligent Robots: Issues and Challenges[J]. IEEE/CAA Journal of Automatica Sinica, 2017, 4(4): 602-609. doi: 10.1109/JAS.2017.7510604

[19] Lijiao Wang, Bin Meng. Distributed Force/Position Consensus Tracking of Networked Robotic Manipulators[J]. IEEE/CAA Journal of Automatica Sinica, 2014, 1(2): 180-186.

[20] Kecai Cao, Bin Jiang, Dong Yue. Distributed Consensus of Multiple Nonholonomic Mobile Robots[IEEE/CAA Journal of Automatica Sinica, 2014, 1(2): 162-170.

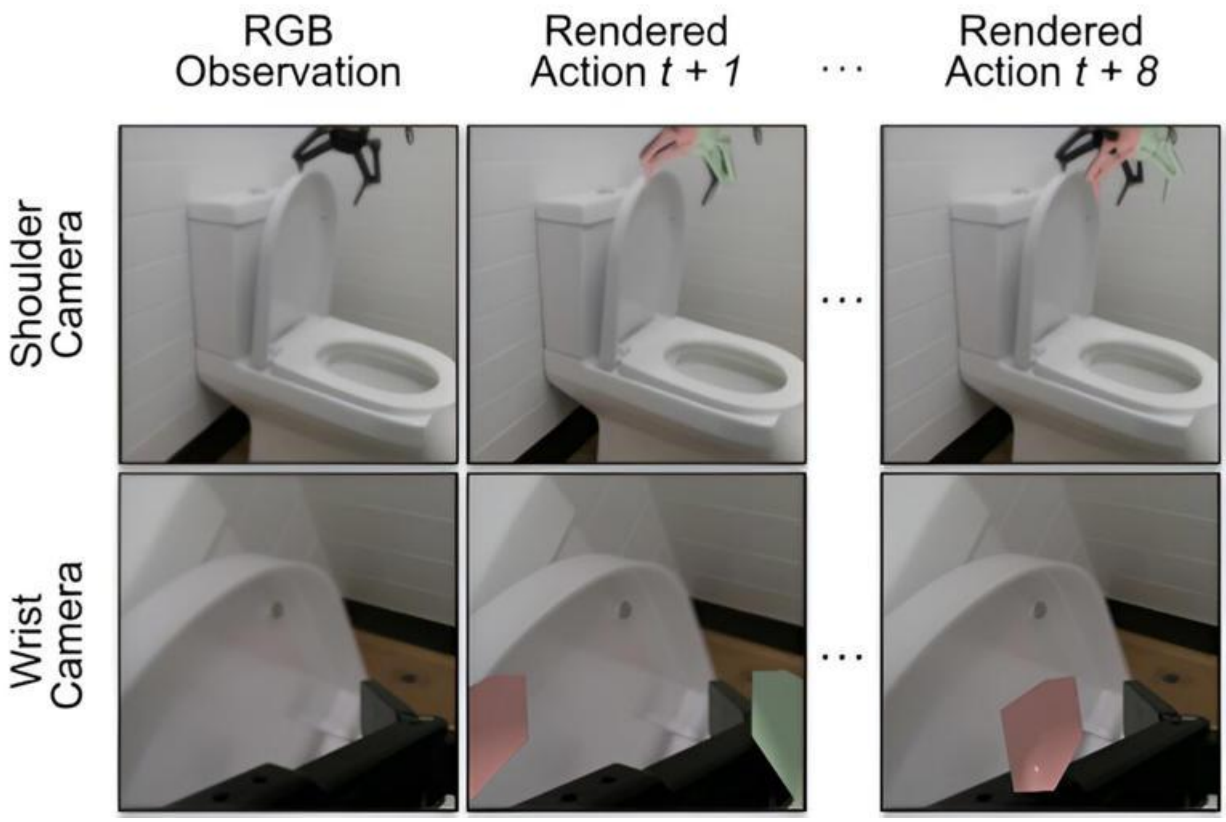
A simpler method to teach robots new skills

A high-level overview of the Render and Diffuse process in the context of a putting the toilet seat down task. Rendered robot grippers are updated iteratively using a learnt denoising process until they represent actions needed to complete the task. Different colors represent different robot actions in the future. Credit: Vosylius et al.© Provided by Tech Xplore

While roboticists have introduced increasingly sophisticated systems over the past decades, teaching these systems to successfully and reliably tackle new tasks has often proved challenging. Part of this training entails mapping high-dimensional data, such as images collected by on-board RGB cameras, to goal-oriented robotic actions.

Researchers at Imperial College London and the Dyson Robot Learning Lab recently introduced Render and Diffuse (R&D), a method that unifies low-level robot actions and RBG images using virtual 3D renders of a robotic system. This method, introduced in a paper published on the *arXiv* preprint server, could ultimately facilitate the process of teaching robots new skills, reducing the vast amount of human demonstrations required by many existing approaches.

"Our recent paper was driven by the goal of enabling humans to teach robots new skills efficiently, without the need for extensive demonstrations," said Vitalis Vosylius, final year Ph.D. student at Imperial College London and lead author. "Existing techniques are data-intensive and struggle with spatial generalization, performing poorly when objects are positioned differently from the demonstrations. This is because predicting precise actions as a sequence of numbers from RGB images is extremely challenging when data is limited."



Visualization of the RGB observations from two different cameras and rendered action representation at time steps t + 1 and t + 8 for the task of putting the toilet seat down. Credit: Vosylius et al.© Provided by Tech Xplore

During an internship at Dyson Robot Learning, Vosylius worked on a project that culminated in the development of R&D. This project aimed to simplify the learning problem for robots, enabling them to more efficiently predict actions that will allow them to complete various tasks.

In contrast with most robotic systems, while learning new manual skills, humans do not perform extensive calculations to determine how much they should move their limbs. Instead, they typically try to imagine how their hands should move to tackle a specific task effectively.

"Our method, Render and Diffuse, allows robots to do something similar: 'imagine' their actions within the image using virtual renders of their own embodiment," Vosylius explained. "Representing robot actions and observations together as RGB images enables us to teach robots various tasks with fewer demonstrations and do so with improved spatial generalization capabilities."

For a robot to learn to complete a new task, it first needs to predict the actions it should perform based on the images captured by its sensors. The R&D method essentially allows robots to learn this mapping between images and actions more efficiently.

"As hinted by its name, our method has two main components," Vosylius said. "First, we use virtual renders of the robot, allowing the robot to 'imagine' its actions in the same way it sees the environment. We do so by rendering the robot in the configuration it would end up in if it were to take certain actions.

"Second, we use a learned diffusion process that iteratively refines these imagined actions, ultimately resulting in a sequence of actions the robot needs to take to complete the task."

Using widely available 3D models of robots and rendering techniques, R&D can greatly simplify the acquisition of new skills while also significantly reducing training data requirements. The researchers evaluated their method in a series of simulations and found that it improved the generalization capabilities of robotic policies.

They also showcased their method's capabilities in effectively tackling six everyday tasks using a real robot. These tasks included putting down the toilet seat, sweeping a cupboard, opening a box, placing an apple in a drawer, and opening and closing a drawer.

"The fact that using virtual renders of the robot to represent its actions leads to increased data efficiency is really exciting," Vosylius said. "This means that by cleverly representing robot actions, we can significantly reduce the data required to train robots, ultimately reducing the labor-intensive need to collect extensive amounts of demonstrations."

In the future, the method introduced by this team of researchers could be tested further and applied to other tasks that robots could tackle. In addition, the researchers' promising results could inspire the development of similar approaches to simplify the training of algorithms for robotics applications.

"The ability to represent robot actions within images opens exciting possibilities for future research," Vosylius added. "I am particularly excited about combining this approach with powerful image foundation models trained on massive internet data. This could allow robots to leverage the general knowledge captured by these models while still being able to reason about low-level robot actions."

More information: Vitalis Vosylius et al, Render and Diffuse: Aligning Image and Action Spaces for Diffusion-based Behaviour Cloning, *arXiv* (2024). DOI: 10.48550/arxiv.2405.18196

28,000 Year Nuclear Waste Battery? Diamond Batteries Explained

Given the relatively short lifespan, overheating, and battery cell supply issues of current battery technologies, they can't be used everywhere. Take satellites, high-altitude drones, healthcare, or even spacecraft, all of which require energy storage with a very long life. But some companies are claiming that diamond battery technology can kill two birds with one stone: creating energy storage that could last for thousands of years by putting nuclear waste to use… potentially powering everything from EVs to cellphones. Is this the holy grail of battery technology or hype; and more importantly, is it safe? Let's explore Nano Diamond Batteries and where this might be going.

Modern life relies on mobile battery-powered devices: at work, at home, at school, and while traveling. We need batteries for communication, transportation, storing energy from renewables like solar and wind, you name it … and it's undeniable that lithium-ion batteries have opened up a world of possibilities.

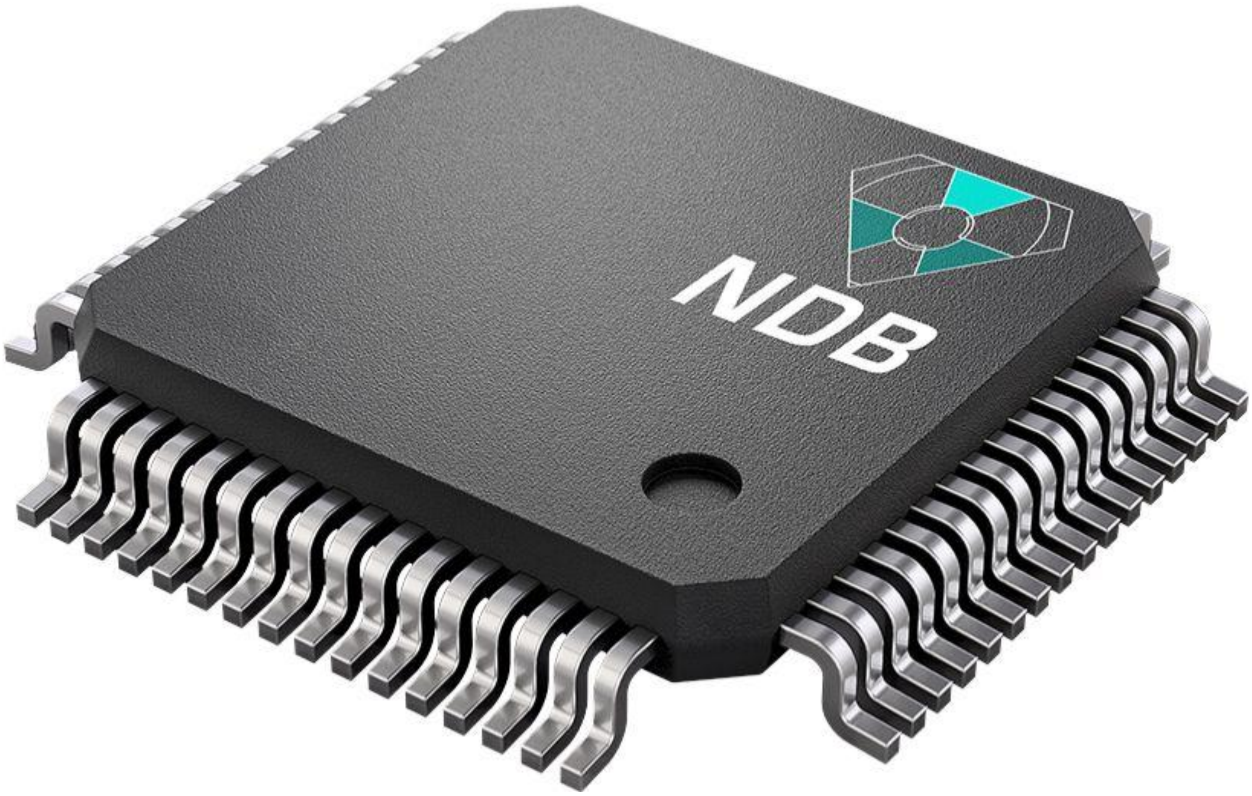
Even though we've seen significant progress with the lithium technology over the past few decades, challenges such as overheating, expensive casings, short lifespan, and underperformance in extreme temperatures still need to be overcome. So the quest for the holy grail of batteries continues.

Aiming to reach carbon neutrality in the next few decades, batteries and renewable power sources need to evolve alongside each other to solve this puzzle. The International Renewable Energy Agency (IRENA) estimates that stationary battery storage will grow from only 2 gigawatts (GW) worldwide in 2017 to around 175 GW in 2030. But batteries aren't the only way to compensate for the intermittent operation of solar and wind. We also have nuclear power. [1]

Nuclear accounted for 10.3% of the world's electricity generation in 2019. [2] It's widely considered to be a stable, carbon-friendly energy source that can be used to support the intermittency of other renewables. But besides being expensive and having long construction times, the unresolved problem of what to do with long-lived radioactive waste is crucial for its development. There's a lot of "not in my backyard" to that debate. If you're interested, I have an episode on Small Modular Reactors that gets into the future of nuclear power. As of today in the U.S., there are 96 commercial nuclear power reactors currently operating, and more than 90,000 metric tons of highly radioactive nuclear waste, including spent fuel and other material. [3]

Pulling together the challenges of conventional batteries and the problems derived from nuclear waste, a new technology called Nano Diamond Battery Technology is being touted as an energy-disruptive innovation.

NDB, a California-based start-up made headlines when it announced that it completed two proof-of-concept tests of its nano diamond battery, made from nuclear waste encased in artificial diamond. But the root of this energy storage technology is known as betavolatics, which is powered by beta decay and goes back to the 1950s.



In 1953, Paul Rappaport proposed the use of semiconductor materials to turn the energy from beta decay into electricity. Unlike common electricity-generation technologies that utilize hydro or wind turbines to spin copper coils within magnets to produce an electric current, betavoltaic devices can generate current when placed close to a radioactive source.

Imagine placing a semiconductor material, like Silicon, in a box with Strontium-90, which is a radioisotope produced from nuclear fission. It has a half-life of almost 30 years.[4] A semiconductor material, like Silicon, can both act as an isolator or conductor depending on the conditions it's subjected to, like temperature, light, or electric current. It's actually very similar to how solar cells work when collecting solar radiation. In this case, the radioactive element emits beta particles that separate electron and hole pairs in the semiconductor (holes collect on the positive side and electrons collect on the negative side). Bridging the two sides allows the electrons and holes to find each other resulting in an electric current … in short, this turns radiation into electricity. [5] [6]

Using this principle, in 2016, researchers from the University of Bristol unveiled the world's first known diamond nuclear battery, which is based on this betavoltaic concept. Tom Scott, Professor in Materials at the University of Bristol, described the advantages as the emission free, long-term production of clean energy from nuclear waste.[7] [8]

A great portion of nuclear waste is graphite, which is used as a moderator and reflector in a nuclear reactor. The graphite becomes radioactive over time because of its exposure to radiation.

And depending on the reactor type, the graphite blocks can be extremely large and heavy, as well as irradiated with long-lived radioisotopes, which makes graphite expensive and tricky to dispose of or recycle.[9]

The reason why graphite is important here is that radioactive graphite contains Carbon-14 (C-14), which turns into harmless Nitrogen-14, an anti-neutrino, and an energetic electron — aka a beta-decay electron. But that's already TMI … I'm not going to turn this into a chemistry class. I'd probably flunk it.

The idea behind the research from the University of Bristol is to manufacture batteries that can harness this by-product of C-14 as energy. In its gas form at low pressure and elevated temperatures, you can convert it into a radioactive diamond. Then for safety you encapsulate it again in a non-radioactive diamond layer. So it's a radioactive diamond … in a diamond. Even though the researchers say that only a small level of radioactivity is detected near their diamond, would you really want to use a nuclear powered pacemaker inside your body? [10] [11] Actually … there were Plutonium powered pacemakers, but that's a different video.[12]

Even though we typically equate nuclear power to great amounts of energy being produced, these betavoltaic batteries can only generate power in the range of microwatts, which is why headlines and press releases about NDB batteries have been overselling it. This is not the future of electric vehicles. If their breakthrough proves to be true, it has some potential … for very targeted scenarios.

The difference between the batteries from Bristol to NDB's is in the layers of the encasing diamond. While the researchers of Bristol used only a diamond layer to protect the radioactive diamond, NDB combines multiple layers of paneled nano diamonds to protect the core. These micro-sized single crystal diamonds are very good at conducting heat, so they move heat away from the radioactive isotope materials so quickly that the transaction generates electricity.[13] [8]

There are several concepts to ensure safety, but there's still a lot of questions around this since we haven't seen any test results from the company yet. But a couple of those things are the diamond encapsulator, which is the most thermally conductive and hardest material available, in addition to containing the radiation within the device.

Next up is the Lock-in System, which helps to prevent proliferation of dangerous nuclear isotopes like Pu-238 and U-232. According to NDB, their battery uses an ion implantation mechanism that prevents it being used for purposes other than power generation. [14] [15]

Besides these safety claims, the company says its technology has a maximum lifespan of 28,000 years and could one day become a source of low-carbon power for anything that needs it – from EVs to smartphones. Although this technology looks awesome, it's still highly questionable since the power coming from betavoltaics is so low. Remember, microwatts low.

According to a report, the proof-of-concept design was evaluated by the Lawrence Livermore National Laboratory, which reported a 40% charge improvement in efficiency over a standard diamond. But I couldn't find any information on how Lawrence Livermore National Laboratory tested the proof-of-concept.

Most of the claims have no hard evidence or proof yet, other than what NDB has reported. NDB doesn't fully explain what happens to the heat it generates during energy conversion other than to describe thermal vents to dissipate heat. [16]

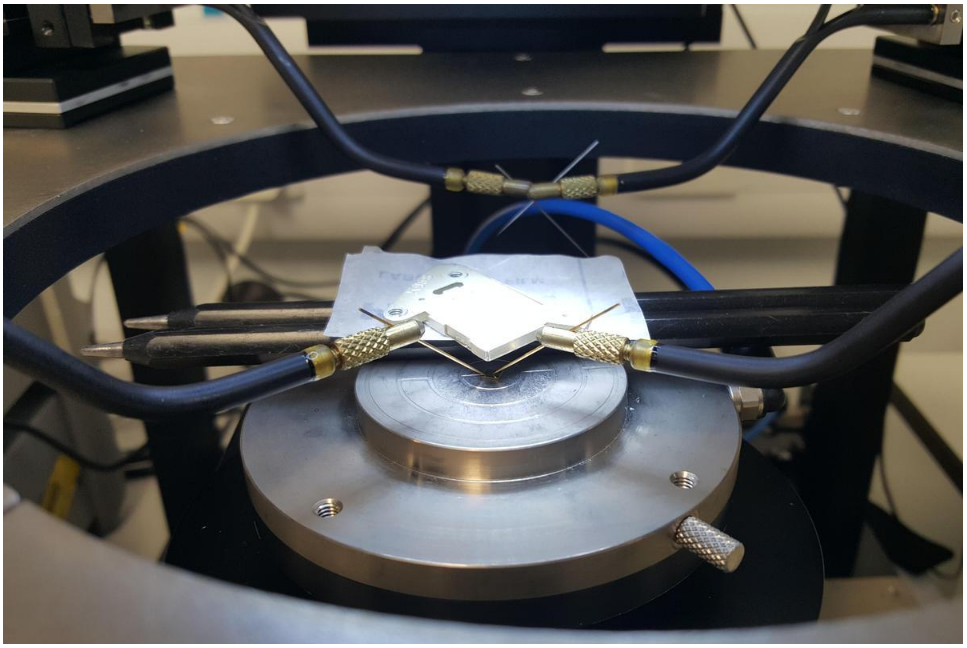
The company mentions several possible applications in their website like consumer electronics, automotive, medical devices, aerospace, but we still don't have precise specifications. Yet, an image of the battery shows a power level of 100 microwatts.[17] It's important to drive that point home. It's highly unlikely to power an electric vehicle, let alone an iPhone at microwatt scale. But, it doesn't mean the tech doesn't work for more appropriate applications. If enough of these battery cells were combined, they could power small LED displays or devices that require low power, like medical or communication devices … think internet of things (IOT) and pacemakers. But powering EVs that demand an insane amount energy is where media coverage went a little overboard.

So back in the land of reality where do the benefits of this technology make the most sense? And is there a market for it?

Well, the company hopes to start selling the battery to commercial partners, including space agencies for long duration missions by 2023. [18]

In addition, NDB isn't alone in nuclear diamond battery game. The scientists at Bristol saw a great opportunity in extracting and repurposing nuclear waste material, but without overselling it.

They spun off Arkenlight, a company formed to take on the commercialization of their diamond battery concept. [19]



Morgan Boardman, the new company's CEO says:

"…It is a very novel approach, which we find that people like because it's sort of a cosmic rag-and-bone man narrative…" -Morgan Boardman

He also points out that the technology can help with the carbon emissions challenge:

"…With the resources used to manufacture, say, an AAA battery, we would offset nearly 2.5kg of carbon in the manufacture of an equivalent energy density of diamond batteries…" -Morgan Boardman

Unlike NDB, Arkenlight doesn't claim that their batteries will power cars or even laptops. That's because they provide thousands of times less power than a conventional AA battery – although they will last thousands of times longer. Arkenlight's power cells would take about 5,000 years to reach 50% discharge. The company sees their batteries powering small detectors, wireless IoT devices/sensors or medical implants. [19]

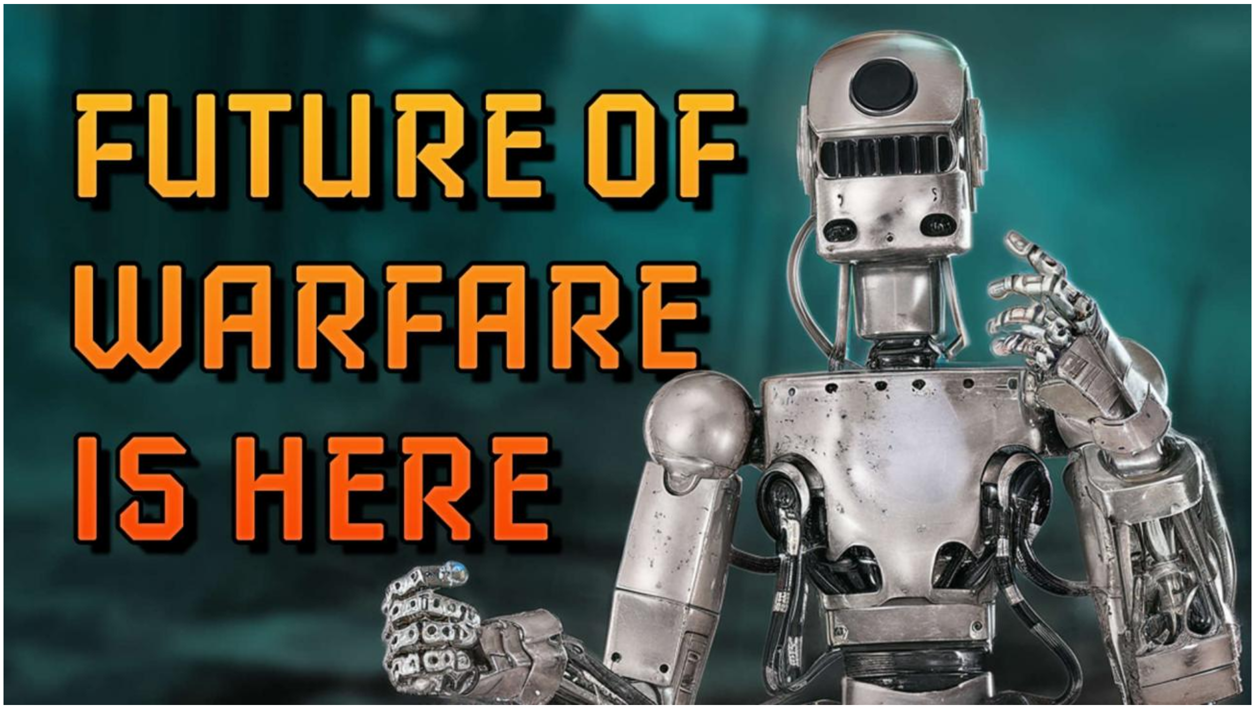
It can be mechanically stacked in series or parallel for greater power, and can be paired with capacitors for intermittent high power use cases. [20] [21]

In 2018, Bristol researchers did an interesting experiment to test out the strength and durability of their diamond batteries, placing them at the top of a volcano. In the experiment, a prototype of Arkenlight betavoltaics was used to power sensors inside a remote-monitoring station, known as a ‘dragon egg.’ The eggs were designed to be placed on an active volcano by drone in order to measure humidity, vibrations, and the emissions of toxic gases. They could remain in service for months without depleting their energy. [22]

Arkenlight aims to establish a factory at one of the several decommissioned nuclear power plants in the South West of England, or possibly North Wales. That way, the company has easy access to carbon-14 isotopes for battery manufacturing. Boardman estimates that their carbon-14 batteries will begin appearing in devices around 2024 if everything goes well. [19]

In terms of challenges, the use of radioactive material complicates matters, so manufacturing them involves a significant amount of care and safety procedures you wouldn’t have with a typical chemical battery. While the process is made safe, the safety infrastructure required to produce it, and governmental permissions, come with big costs.

Even though the researchers from both Bristol University and NDB claim that nuclear batteries have small or no radioactivity level due to the diamond containment, I’m not sure if I’d feel comfortable having a nuclear powered cellphone even if it was possible at this point. Putting aside the overhyped headlines, there’s still some interesting promise and use cases for diamond batteries … even though they’re still in their theoretical phase. We’re going to need to wait a few more years until NDB and Arkenlight have some real prototypes and solid results to call this one. Not every battery technology has to be a lithium ion killer. It’s okay to have an exciting breakthrough for a very targeted market, which is what this is.



Gone are the days when military robots were just clunky remote-controlled machines. Today's battlefield is witnessing an extraordinary partnership between soldiers and their mechanical counterparts, each bringing unique strengths to the fight. While humans provide the irreplaceable elements of judgment, creativity, and ethical decision-making, robots take on the most dangerous tasks, from disarming explosives to patrolling hostile territories.

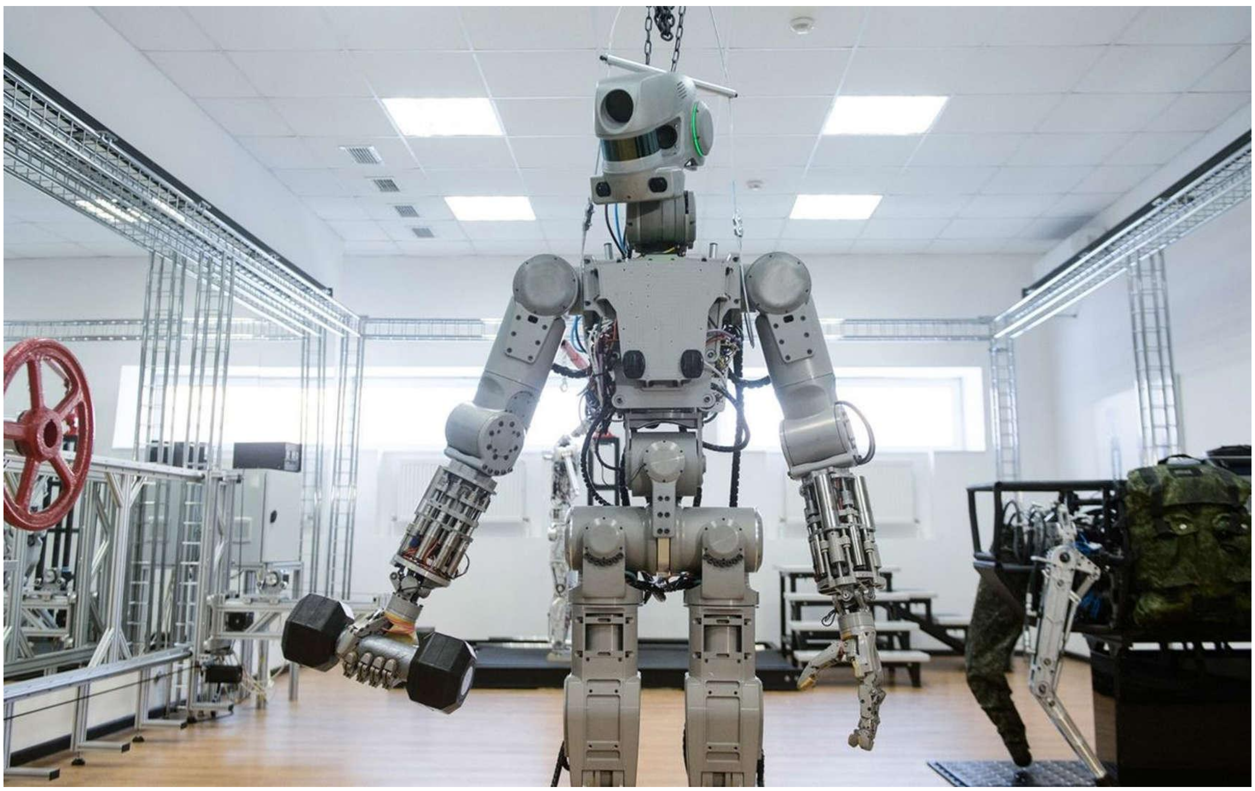
Let's explore some of the most impressive military robots that are changing the face of modern warfare, each designed to tackle specific challenges while working alongside human operators.

The Bionic Yak

The Bionic Yak is a cutting-edge military robot from China, engineered for logistics and reconnaissance missions. Capable of carrying up to 160 kg of cargo, it traverses challenging terrains like snow and rocky paths with ease. With a speed of 10 km/h, the Bionic Yak is equipped with advanced sensors for gathering tactical data on the battlefield, making it an indispensable tool for remote and hard-to-reach military operations.

FEDOR

FEDOR is a humanoid robot designed by Russian engineers to handle extreme scenarios, including rescue missions and space exploration. Standing 180 cm tall and weighing 105 kg, FEDOR can operate autonomously or via remote control. It boasts impressive versatility, performing tasks such as tool handling, vehicle operation, and even executing advanced movements like splits. Despite setbacks due to sanctions, FEDOR continues to showcase the innovative potential of Russian robotics.

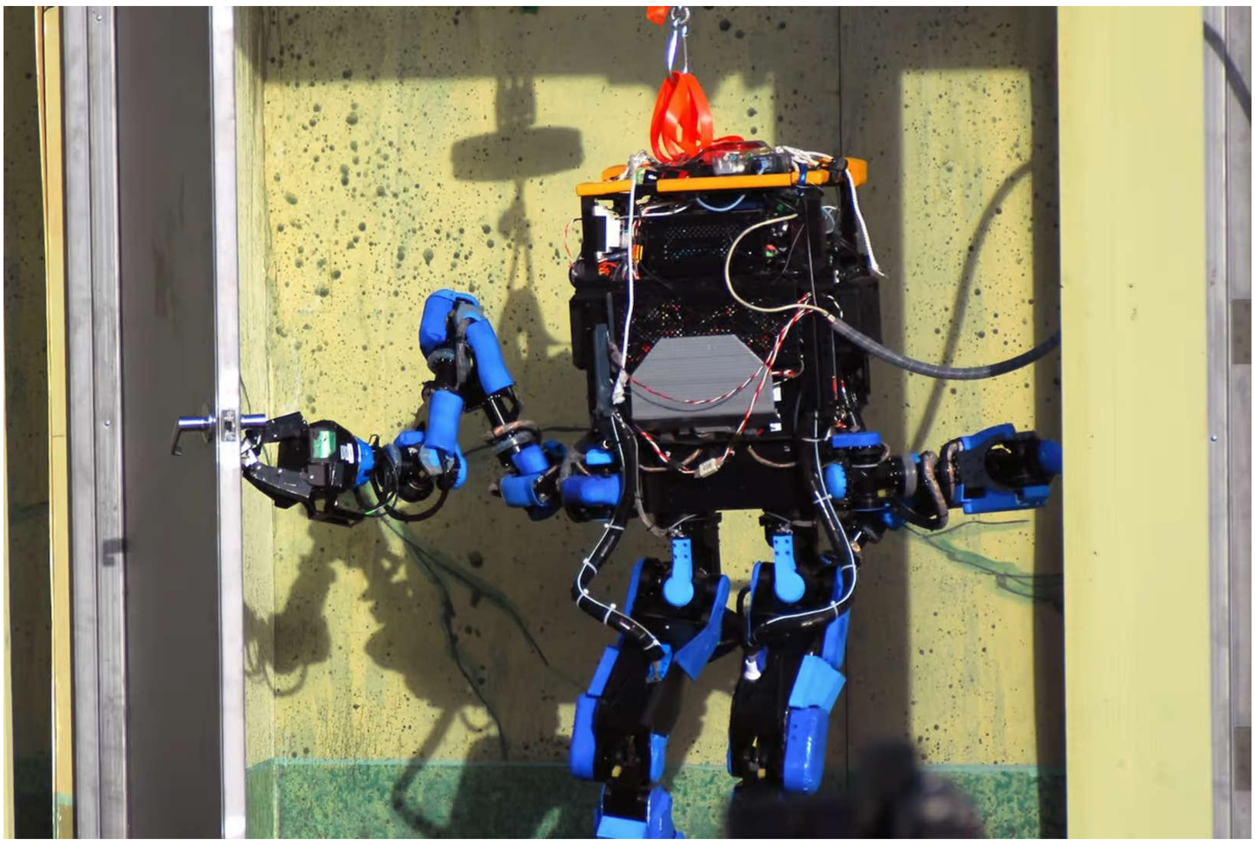


EOD Robot

The EOD Robot is a specialized machine designed for the safe disposal of explosive ordnance. Widely used across the globe, it features advanced cameras and sensors that allow it to identify and neutralize explosive devices remotely. By providing real-time video and feedback to operators, the EOD Robot minimizes risks to military personnel and civilians, proving its value in high-stakes operations.

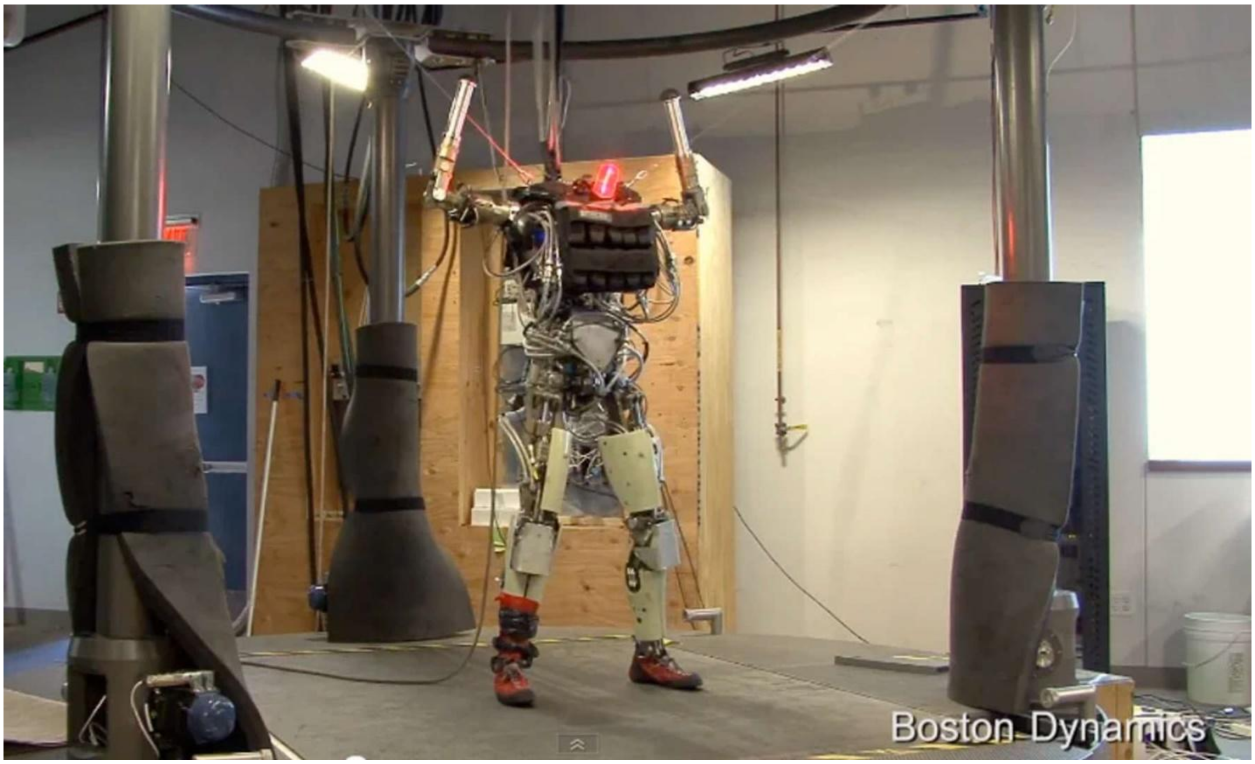
SCHAFR

Japan's SHAFR robot gained recognition during the DARPA Robotics Challenge, where it excelled in tasks such as driving vehicles and navigating complex obstacles. Weighing 95 kg and standing 1.48 m tall, this agile humanoid is designed for military applications in urban environments. SHAFR's ability to mimic human movements demonstrates its potential to enhance operational capabilities in various scenarios.



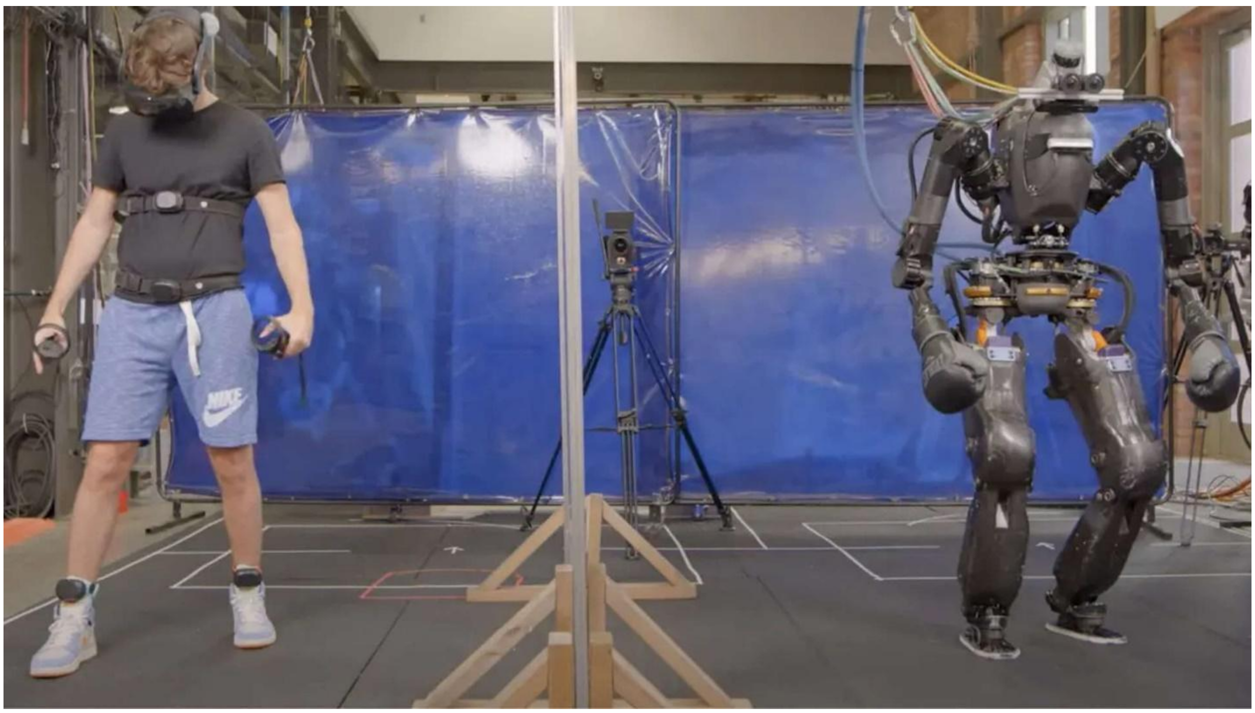
Petman

Developed by Boston Dynamics, Petman is a humanoid robot created to test military uniforms and protective gear. It mimics human physiology with realistic movements such as walking, squatting, and even sweating to simulate real-world conditions. While its primary role is gear testing, future iterations could see Petman playing an active role in combat or hazardous fieldwork.



Nadia: The Boxing Robot

IHMC Robotics' Nadia is a highly sophisticated humanoid robot built for dangerous environments. With 29 flexible joints, it performs complex movements, making it ideal for rescue missions or space exploration. Although currently operated by human controllers, Nadia's intuitive design aims to optimize efficiency in perilous situations, with potential future applications in military operations.

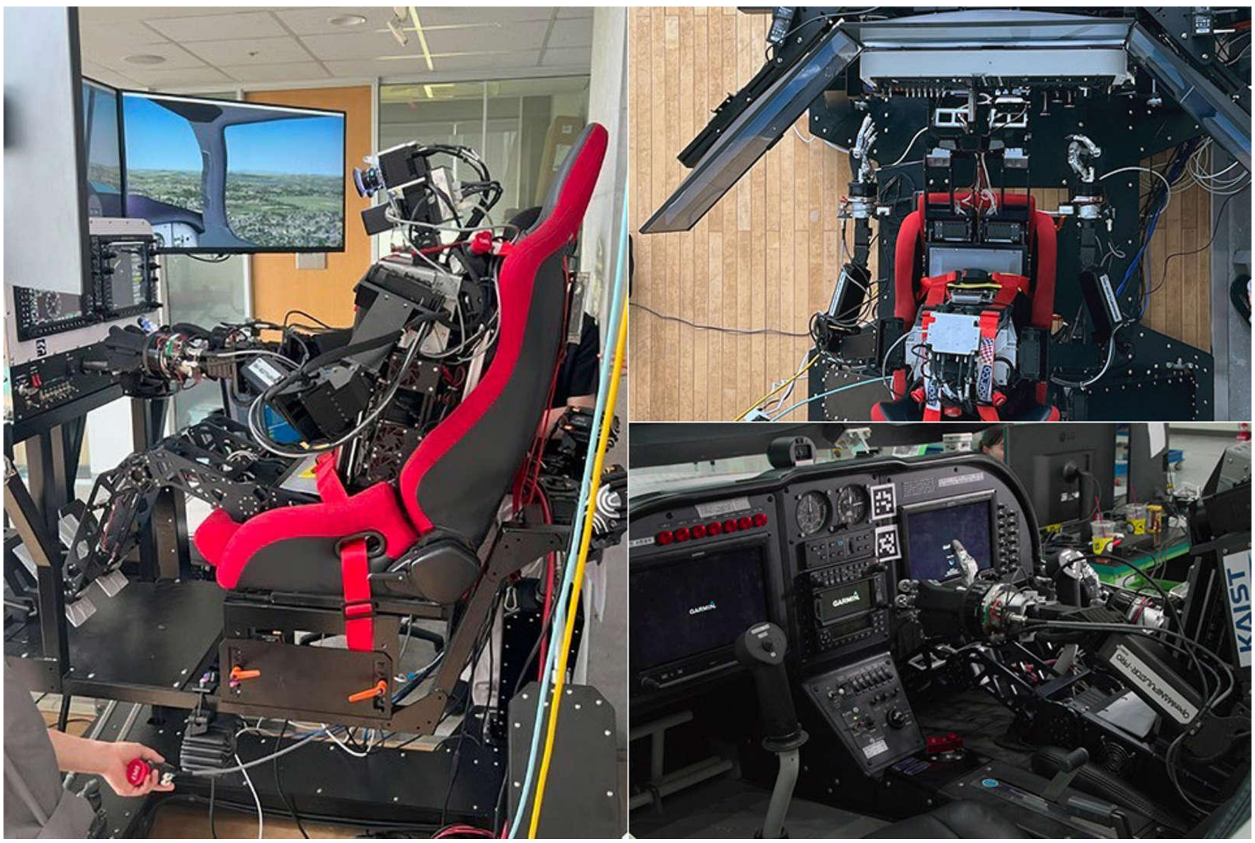


Avatar Robots

Russia is developing Avatar Robots aimed at replacing soldiers on the battlefield. These robots are designed to function seamlessly within human-built environments, providing tasks like first aid, vehicle operation, and infrastructure interaction. The ultimate goal is to create autonomous machines that can take on combat risks, protecting human lives.

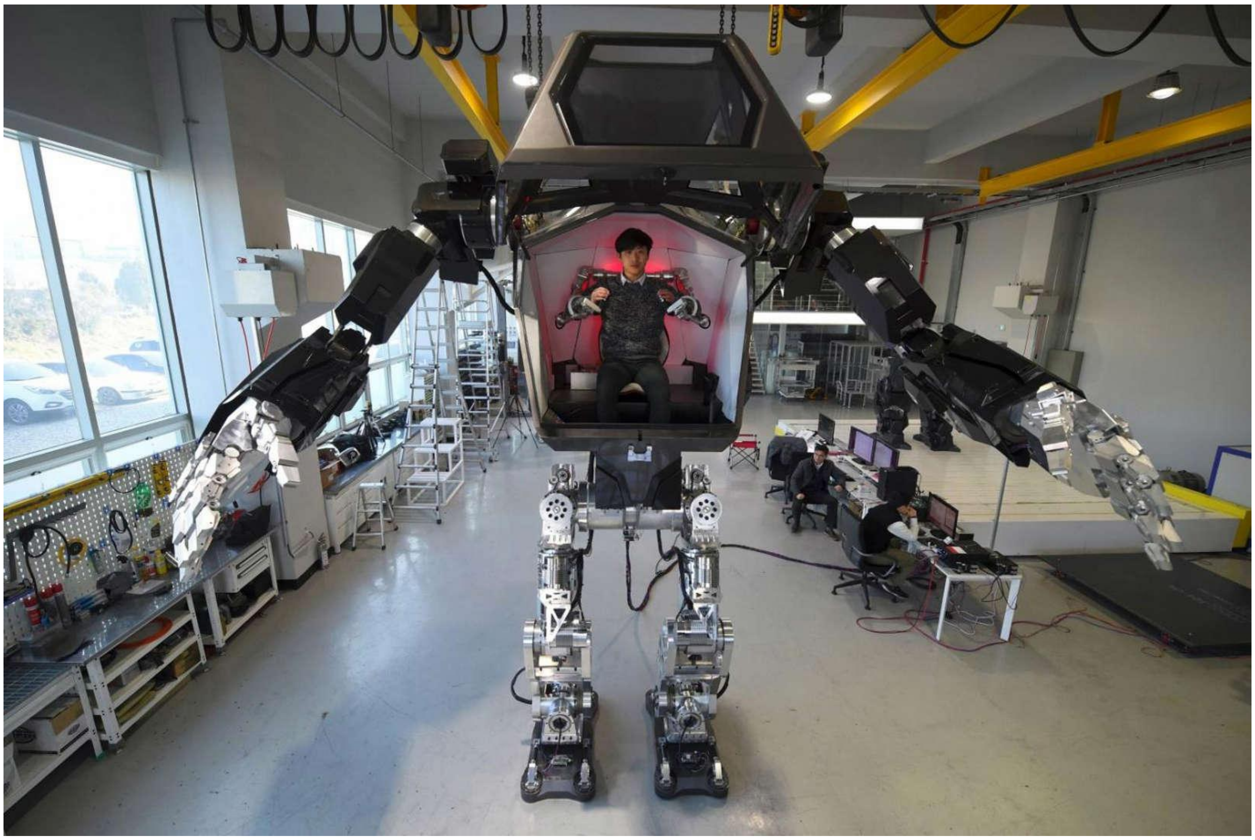
The Humanoid Pilot

The PIBOT robot from South Korea is the first humanoid pilot capable of controlling human-operated transportation systems. Its design allows it to sit in standard seats and operate vehicles with precision. Equipped with AI, the PIBOT reacts to emergencies swiftly, making it a groundbreaking addition to military aviation and automated transport systems.



Method 2

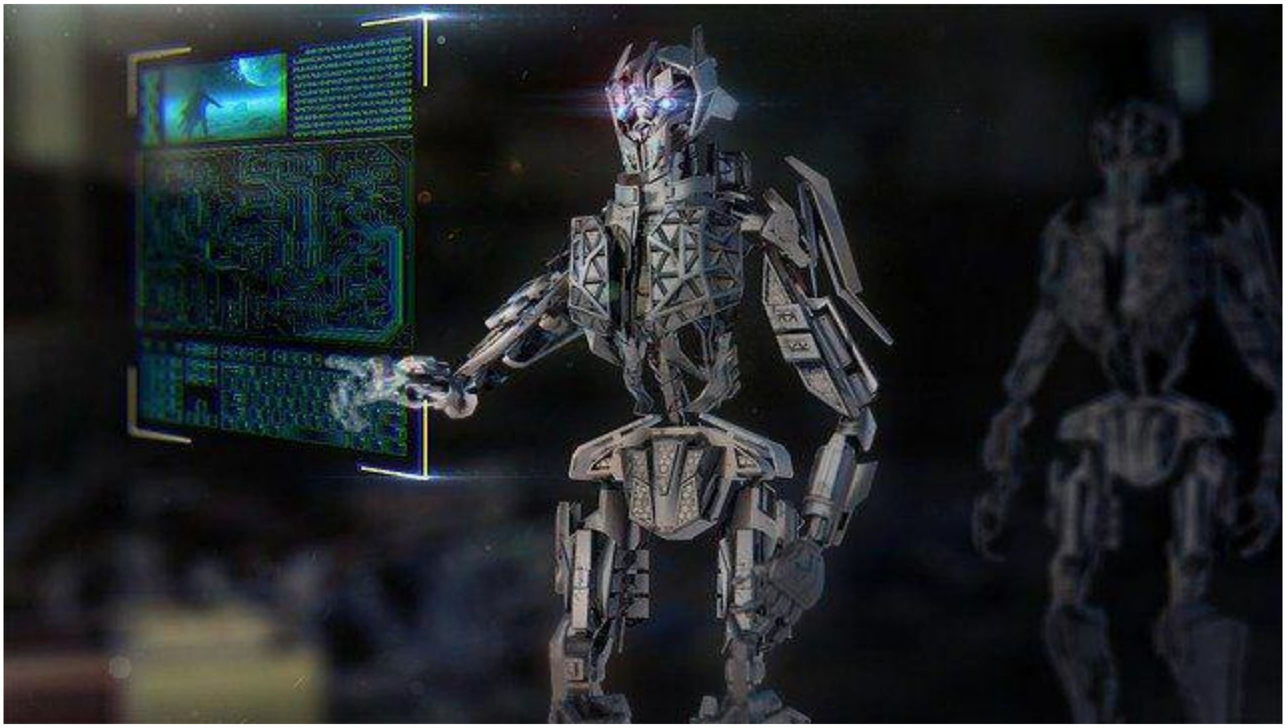
Method 2 is a massive robot developed in South Korea, designed to tackle hazardous environments. Weighing 1.5 tons and standing nearly 4 meters tall, it's built for both military and industrial use. Though still in development, Method 2 highlights the potential for large-scale robots to take on high-risk roles in combat and support missions.



Robotic Combat Dogs

Robotic combat dogs are a new wave of innovation, with models equipped with automatic rifles mounted on their backs. These robots can operate autonomously or be remotely controlled, and they feature built-in cameras with a 360° field of vision. While still undergoing testing, robotic combat dogs are poised to carry out missions in diverse terrains, marking a significant leap in autonomous warfare technology.

US scientists may have developed the first robot syllabus that allows machines to transfer skills without human intervention



Ein Robo Advisor verwaltet das investierte Geld frei von allen Emotionen und versucht, durch rational vernünftige Entscheidungen dabei den Gewinn zu maximieren.© Pixabay.com © Computerizer CCO Public Domain

- **Robots struggle to learn from each other, and rely on human instruction**
- **New research from UC Berkeley shows that the process could be automated**
- **This would eliminate the struggles of manually training robots**

Despite robots being increasingly integrated into real-world environments, one of the major challenges in robotics research is ensuring the devices can adapt to new tasks and environments efficiently.

Traditionally, training to master specific skills requires large amounts of data and specialized training for each robot model - but to overcome these limitations, researchers are now focusing on creating computational frameworks that enable the transfer of skills across different robots.

A new development in robotics comes from researchers at UC Berkeley, who have introduced RoVi-Aug - a framework designed to augment robotic data and facilitate skill transfer.

The challenge of skill transfer between robots

To ease the training process in robotics, there is a need to be able to transfer learned skills from one robot to another even if these robots have different hardware and design. This capability would make it easier to deploy robots in a wide range of applications without having to retrain each one from scratch.

However, in many current robotics datasets there is an uneven distribution of scenes and demonstrations. Some robots, such as the Franka and xArm manipulators, dominate these datasets, making it harder to generalize learned skills to other robots.

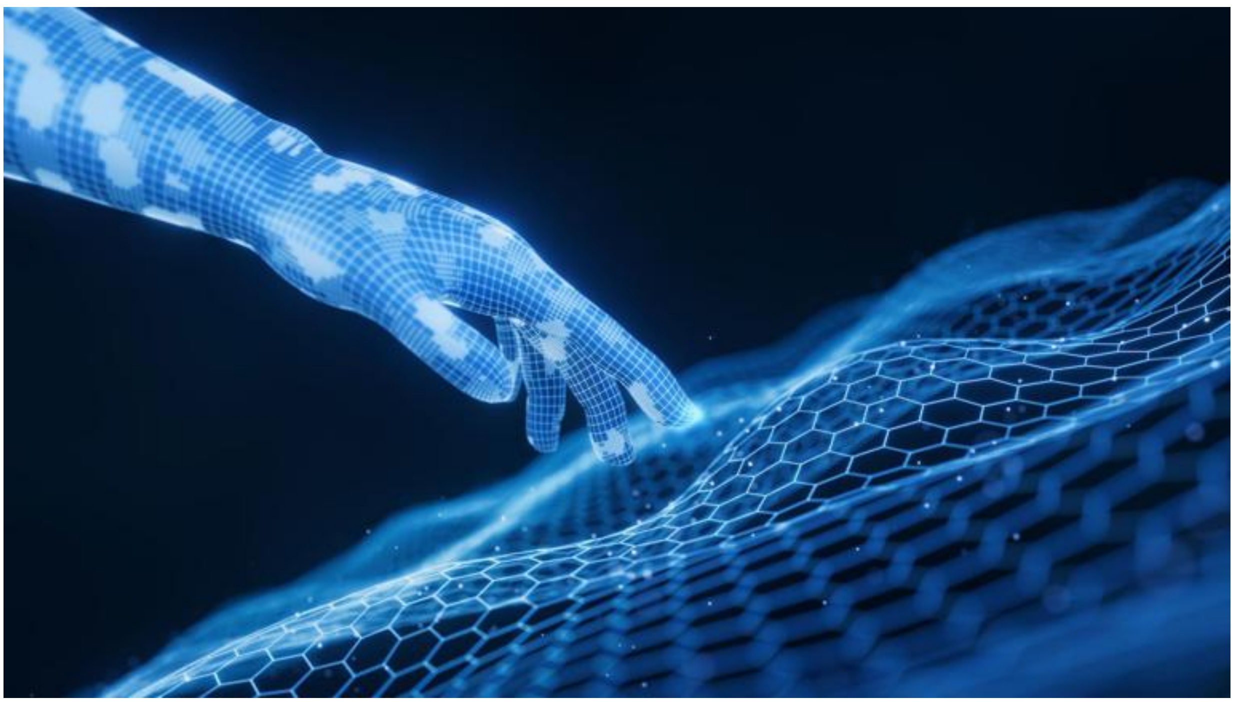
To address the limitations of existing datasets and models, the UC Berkeley team developed the RoVi-Aug framework which uses state-of-the-art diffusion models to augment robotic data. The framework works by producing synthetic visual demonstrations that vary in both robot type and camera angles. This allows researchers to train robots on a wider range of demonstrations, enabling more efficient skill transfer.

The framework consists of two key components: the robot augmentation (Ro-Aug) module and the viewpoint augmentation (Vi-Aug) module.

The Ro-Aug module generates demonstrations involving different robotic systems, while the Vi-Aug module creates demonstrations captured from various camera angles. Together, these modules provide a richer and more diverse dataset for training robots, helping to bridge the gap between different models and tasks.

"The success of modern machine learning systems, particularly generative models, demonstrates impressive generalizability and motivated robotics researchers to explore how to achieve similar generalizability in robotics," Lawrence Chen (Ph.D. Candidate, AUTOLab, EECS & IEOR, BAIR, UC Berkeley) and Chenfeng Xu (Ph.D. Candidate, Pallas Lab & MSC Lab, EECS & ME, BAIR, UC Berkeley), told *Tech Xplore*.

'This is a marriage of AI and quantum': New technology gives AI the power to feel surfaces for the 1st time



'This is a marriage of AI and quantum': New technology gives AI the power to feel surfaces for the 1st time© Jian Fan via Getty Images

Scientists have given artificial intelligence (AI) the capacity to "feel" surfaces for the first time — opening up a new dimension for deploying the technology in the real world.

Tapping into quantum science, the scientists combined a photon-firing scanning laser with a new AI model trained to tell the difference between different surfaces imaged with the lasers.

The system, outlined in a new study published Oct. 15 in the journal Applied Optics, blasts a series of short light pulses at a surface to "feel" it, before back-scattered photons, or particles of light, return carrying speckle noise — a type of flaw that manifests in imagery. This is normally considered detrimental to imaging, but in this case the researchers processed the noise artifacts using AI — which enabled the system to discern the topography of the object.

"This is a marriage of AI and quantum," study co-author Daniel Tafone, a doctoral candidate at New Jersey's Stevens Institute of Technology, said in a statement.

The team used 31 variations of industrial sandpaper with roughness ranging from 1 to 100 micrometers in thickness — with the thickest roughly the width of a human hair. The researchers then set up the lidar system, which used a laser beam fired in picosecond pulses (1 trillion picoseconds is 1 second).

Related: Computers normally can't see optical illusions — but a scientist combined AI with quantum mechanics to make it happen

Pulses of light passed through transceivers, hit the sandpaper, then rebounded through the system for AI analysis. The back-scattered photons came from different points on the surface and were counted using a single photon detector.

The results achieved an average error of roughly 8 micrometers — but this improved to just 4 micrometers after the AI worked with multiple samples. This is roughly in line with the accuracy of profilometer devices currently in use.

"Interestingly, our system worked best for the finest-grained surfaces, such as diamond lapping film and aluminum oxide," Tafone said in the statement. These materials are often on sandpaper for specific application.

The scientists said that the new method could be used for various applications, including in medical contexts to detect the thickness of moles that may be the precursor to skin cancer.

"Tiny differences in mole roughness, too small to see with the human eye but measurable with our proposed quantum system, could differentiate between those conditions," Yuping Huang, director of Stevens' Center for Quantum Science and Engineering (CQSE), said in the statement. "Quantum interactions provide a wealth of information, using AI to quickly understand and process it is the next logical step.”

A Figure humanoid robot is performing tasks autonomously

Robotics startup Figure recently shared a new video showing several of its humanoid robots performing a task that could be applied to the automotive industry.

Figure completed a trial deployment of its advanced “Figure 02” humanoid robot at a BMW facility in Spartanburg, South Carolina, a few months ago, when the robots were used to insert sheet metal parts into specific fixtures that were then assembled as part of a vehicle’s chassis.

In the new video, California-based Figure said its fully autonomous humanoid robot is capable of carrying out 1,000 placements a day, with the latest version of the machine improving in areas of accuracy and speed over the original design.

“The developments in the field of robotics are very promising,” BMW said at the end of the trial in August. “With an early test operation, we are now determining possible applications for humanoid robots in production.” It added that the robot “can save employees from having to perform ergonomically awkward and tiring tasks.”

The trial also allowed BMW to better understand how it might successfully integrate multi-purpose robots into an existing production system.

Looking ahead, BMW and Figure will work together to improve the robot’s design while preparing it for future applications in auto manufacturing.

Figure unveiled the latest version of its humanoid robot in August, in time for the BMW trial. It features three times the processing power of the original version, improved voice communication, better cameras, microphones, and sensors, and a high-performance battery. It also comes with fourth-generation human-scale hands with 16 degrees of freedom and human-equivalent strength, capable of performing two-handed tasks that require varied and dynamic manipulation, complex grasping, and careful coordination.

While it’s true that highly advanced, multi-axis arm-like robots have been operating in car plants for decades, it’s possible that humanoid robots — like those being developed by Figure, Boston Dynamics, and Tesla — could one day surpass these in areas such as versatility and adaptability, which is particularly important in dynamic manufacturing environments. The hands attached to humanoid robots are certain to become even more dexterous, enabling them to better perform more delicate manipulations than those carried out by more traditional industrial robots. Cognitive abilities, too, will improve over time, with AI helping the robots to act more intelligently for even greater autonomy.

Multi-axis robots certainly excel in specific, repetitive tasks, but humanoid robots look like a more flexible solution for complex, varied environments where human-like interaction and problem-solving abilities are key.

The current crop of humanoid robots aren’t there yet, but it’s exciting to see the advances being made in the sector.

Robots in BMW factories: Revolutionizing the future of work

Humanoid robots in the BMW factory© Youtube

Humanoid robots developed by the company Figure AI demonstrate their capabilities in an impressive recording. These machines successfully perform simple tasks in a BMW factory. Is this a preview of upcoming changes in the labor market?

Just a decade ago, the idea of replacing humans with robots was seen as science fiction. Today, in this era of rapid development in artificial intelligence and robotics, such a vision is becoming increasingly plausible. Evidence of this can be seen in the efforts of the tech giant Boston Dynamics and others.

It turns out that more and more companies are consistently developing their humanoid machines. Take, for example, Tesla's Optimus or the focus of this article, a robot named Figure 02. It is already involved in the automotive production process, performing straightforward manual tasks.

Figure 02 in the BMW factory - what can the robot do?

Figure 02 is a creation by Figure AI that successfully and seamlessly integrates into the BMW car production process. The humanoid robot is powered by electricity and operates efficiently for five hours, during which Figure 02 can perform up to 1,000 operations.

The machine measures 5 feet 6 inches and weighs about 150 pounds. **The greatest advantage of Figure 02 is undoubtedly its dexterity**. A display of its skills is captured in an intriguing recording. Importantly, the footage shows that the robot manufacturer focuses not only on quality but also on quantity—one shot reveals as many as three machines moving parts to designated places.

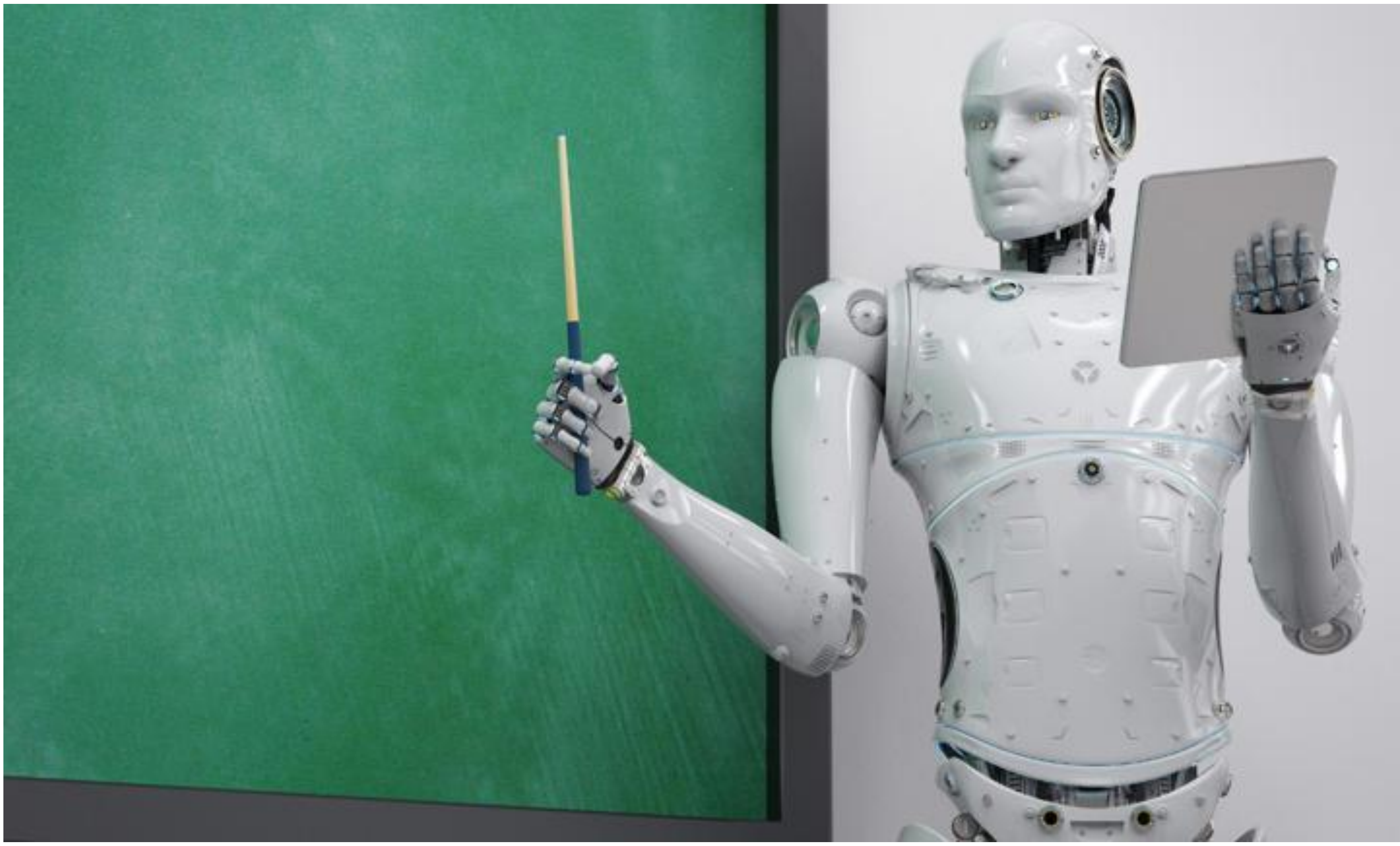
According to "The Sun," this technology has the potential to revolutionize the manufacturing industry, benefiting both companies and consumers worldwide.

Opportunity or threat?

Figure AI boldly declares that it will deliver "millions of useful robots to companies and homes worldwide." The use of such machines on a larger scale will undoubtedly require the market to adapt. The primary concern is the uncertain future of skilled workers.

Nevertheless, the introduction of humanoid robots could also mean an opportunity, as each machine will require appropriate technical support and servicing.

US creates ‘syllabus’ for robots to swap skills at will without human need


US creates ‘syllabus’ for robots to swap skills at will without human need

Engineers have created an innovative framework that enables robots to share skills across models autonomously.

Named RoVi-Aug, it eliminates the need for human intervention in the learning process, simplifying robotic training.

Physical tests reveal that RoVi-Aug trains on enhanced data to work instantly with new robots, regardless of camera angles. Unlike others, it skips extra test-time steps, adapts policies, and learns multi-robot tasks. This boosts skill transfer efficiency and raises success rates by up to 30 percent.

According to the UC Berkeley team, the approach marks a significant step toward developing more independent and adaptable robots.

Adaptive data scaling

Research shows that scaling up data improves robots' ability to learn general and reliable skills. However, robot data is far smaller than those used in advanced AI models for vision and language. Collecting diverse and useful real-world robot data is slow, labor-intensive, and challenging to balance for adaptable training.

Existing models like the Open-X Embodiment (OXE) project combine data from 60 robot datasets to enhance cross-robot learning. This approach helps robots share experiences, improving their capabilities.

According to researchers, the dataset needs to be more balanced, dominated by specific robots like Franka and xArm, and needs diverse camera angles. This causes models to overfit and require adjustments when used with different robots or viewpoints.

To address this, the Mirage algorithm adapts unseen robots by "cross-painting," making them appear like those in training. While effective for zero-shot learning, Mirage has drawbacks: it needs accurate robot models, doesn't support fine-tuning, and struggles with large camera changes.

UC Berkeley's work presents RoVi-Aug, an advanced approach to overcoming the shortcomings of existing robot learning techniques.

RoVi-Aug concentrates on explicitly teaching models to comprehend the interaction between robots and tasks within the data, in contrast to conventional methods that naively co-train on merged datasets from numerous robots.

Advancing robot training

The new framework creates synthetic visual demonstrations that vary by robot type and camera angles, making training more versatile. It includes two main parts: the robot augmentation (Ro-Aug) module, which generates demonstrations with different robotic systems, and the viewpoint augmentation (Vi-Aug) module, which simulates demonstrations from various camera perspectives.

By combining these modules, the framework provides a richer, more diverse training dataset. This approach allows robots to learn from a broader range of scenarios, improving their ability to transfer skills efficiently between different models and tasks while reducing the need for extensive real-world data collection.

The method also lessens the requirement for intensive real-world data collecting while enabling robots to learn from a wider variety of circumstances, enhancing their capacity to transfer skills effectively between various models and jobs.

According to researchers, the approach enhances the robustness and generalizability of policies to handle different robot visuals and camera angles during training, eliminating reliance on precise test-time adjustments like cross-painting pipelines.

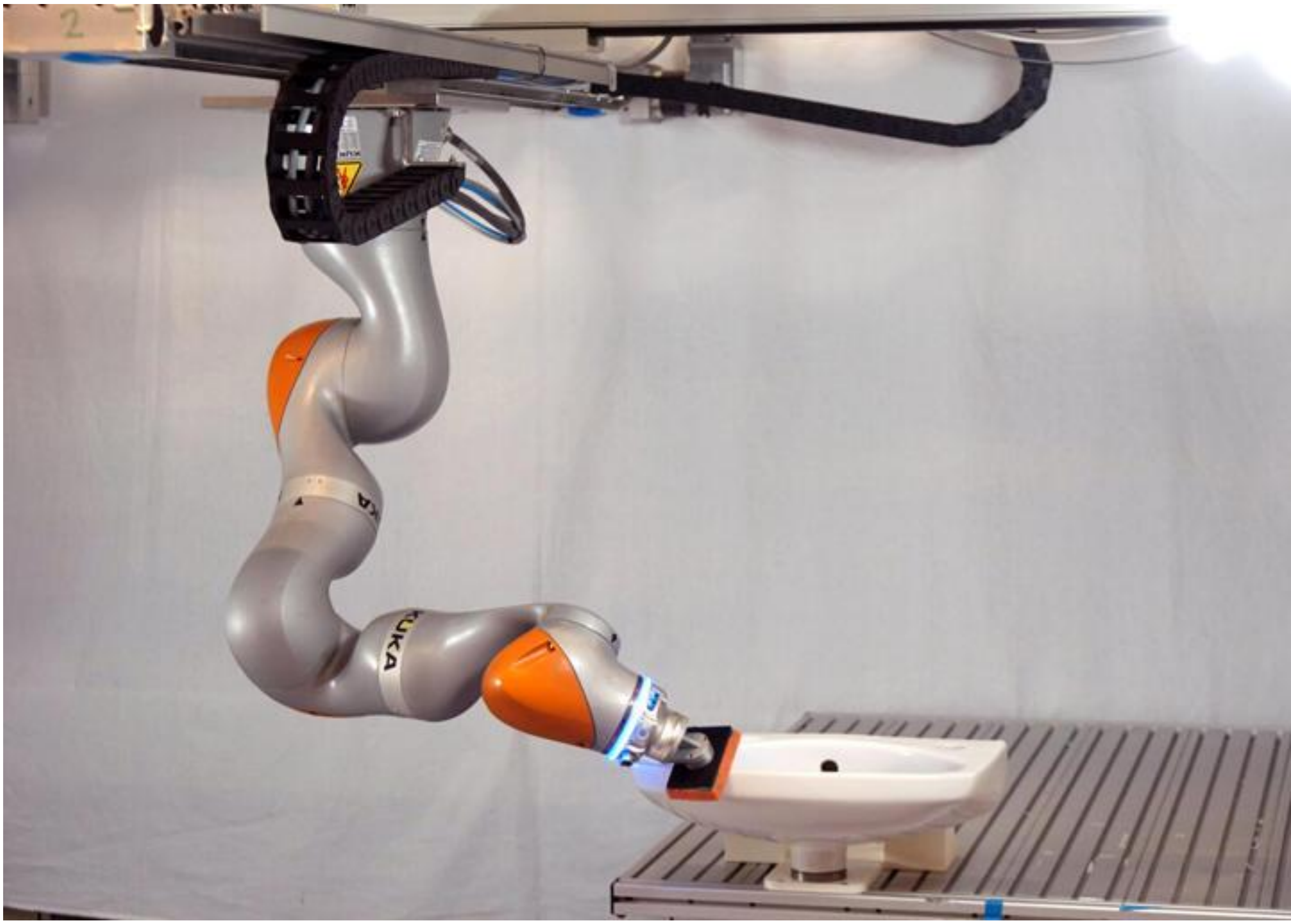
Unlike methods such as Mirage, RoVi-Aug does not require known camera matrices and supports policy fine-tuning, which significantly enhances performance in complex tasks.RoVi-Aug enhances the sample efficiency of fine-tuning while facilitating the learning of multi-robot and multi-task policies by co-training on both original and augmented datasets.

Although RoVi-Aug bridges robot datasets and improves skill transfer, researchers note that it has drawbacks. Future research could address background changes, improve viewpoint synthesis with robotics data, unify robot-pair models, and improve artifact handling.

Generalization may be further enhanced by extending to different grippers, such as multi-fingered hands, and integrating with object and task augmentation.

The details of the UC Berkeley team's research were pre-published on *ArXiv*

Washbasin-cleaning robot can imitate human motions and adapt its knowledge flexibly to different situations



Helper in the bathroom: a robot arm at TU Wien. Credit: TU Wien

Robots are supposed to do boring or unpleasant jobs for us. However, tedious tasks such as cleaning the bathroom are challenging to automate. How is it possible to calculate the movement of a robot arm so that it can reach every part of a washbasin? What if the basin has unusually curved edges? How much force should be applied at which point?

Simulating dirt with blue color. Credit: TU Wien

It would be highly time-consuming to precisely encode all these things in fixed rules and predefined mathematical formulas. A different approach has been taken at TU Wien: a human shows a robot several times what it should do. A specially prepared sponge is used to clean the edge of a sink.

By watching the human, the robot learns how cleaning works and can flexibly apply this knowledge to differently shaped objects. The work has now been published at IROS 2024 in Abu Dhabi.

Cleaning, sanding, polishing

Cleaning is just one type of surface treatment. Many other activities that play an essential role in industry are technically very similar—such as sanding or polishing surfaces, painting, or applying adhesives.

"Capturing the geometric shape of a washbasin with cameras is relatively simple," says Prof Andreas Kugi from the Automation and Control Institute at TU Wien. "But that's not the crucial step. It is much more difficult to teach the robot: which type of movement is required for which part of the surface? How fast should the motion be? What's the appropriate angle? What's the right amount of force?"

People learn these things through experience and imitation. "In a workshop, someone might look over the apprentice's shoulder and say, You need to press a little harder on that narrow edge," says Christian Hartl-Nesic, head of the Industrial Robotics group in Andreas Kugi's team. "We wanted to find a way to let the robot learn in a very similar way."

The demo version of a cleaning sponge

A special cleaning tool was developed for this purpose. A cleaning sponge fitted with force sensors and tracking markers was used by humans to repeatedly clean a sink—but only the front edge. "We generate a huge amount of data from a few demonstrations, which is then processed so that the robot learns what proper cleaning means," explains Christian Hartl-Nesic.

This learning process is made possible by an innovative data processing strategy developed by the research team at TU Wien. It combines several existing techniques from the field of machine learning: the measurement data is first statistically processed, and the results are used to train a neural network to learn predefined movement elements (so-called 'motion primitives'). The robot arm is then optimally controlled to clean the surface.

This innovative learning algorithm enables the robot to clean the entire sink or other objects with a complex surface after the training, even though it has only been shown how to clean a single edge of the sink.

"The robot learns that you have to hold the sponge differently depending on the shape of the surface, that you have to apply a different amount of force on a tightly curved area than on a flat surface," explains Ph.D. student Christoph Unger from the Industrial Robotics group.

The vision: All workshop robots learn together

The technology presented applies to many processes, whether sanding wooden work in joinery, repairing and polishing paint damage on vehicle bodies, or welding sheet metal parts in metalworking shops. In the future, the robot could be placed on a mobile platform to be used as a useful helper anywhere in a workshop.

Such robots could then even share their knowledge with other robots.

"Let's imagine many workshops use these self-learning robots to sand or paint surfaces. Then, you could let the robots gain experience individually with local data. Still, all the robots could share the parameters they learned with each other," says Andreas Kugi.

Private data—such as the specific shape of a particular workpiece—would remain private, but essential basic principles would be exchanged to further improve the capabilities of all robots. This is referred to as "federated learning."

Numerous tests at TU Wien have proven the sink-cleaning robot's flexibility. The technology is also already causing a stir internationally.

At IROS 2024 (14 to 18 October 2024), a conference with over 3,500 submitted scientific papers, TU Wien's work was awarded the Best Application Paper Award and thus voted one of the top innovations of the year.

More information: Christoph Unger et al. ProSIP: Probabilistic Surface Interaction Primitives for Learning of Robotic Cleaning of Edges. www.acin.tuwien.ac.at/file/pub ... _print/unger2024.pdf

Provided by Vienna University of Technology

US Special Forces to get combat robots to advance operational capability

US Special Forces to get combat robots to advance operational capability

KNDS France Robotics announced a contract to deliver 10 NERVA-LG robotic systems to the US Special Forces, describing the order as an example of its ability to meet the specialized needs of military units.

In recent years, KNDS's robotics division, through Nexter Robotics, has broadened its range to include advanced unmanned ground vehicles (UGVs) designed for various military and security missions.

Advanced system enhances intelligence gathering

The NERVA-LG is a lightweight, durable, and versatile robotic system designed for military operations. Equipped with four cameras and a microphone, it gathers intelligence over distances of up to 1,000 meters in open areas and 300 meters in urban settings.

The system is fitted with advanced imaging and sensor technology to detect threats like IEDs and CBRN hazards, all while maintaining a discreet profile. Its compact size and low thermal signature allow it to operate unnoticed, making it ideal for covert missions focused on stealth and intelligence gathering. The robot's ability to carry various payloads, such as cameras or detection devices, enhances its versatility, making it a valuable asset for Special Forces in high-risk environments.

As the company further explains, the NERVA-LG's adaptability is showcased through over 20 available "mission kits," enabling it to handle tasks like CBRN detection, IED management, victim assistance, and close combat support. KNDS also added that its semi-autonomous features minimize the need for manual operation, helping personnel focus on critical mission

Versatile robot set to transform military operations

As unmanned systems become increasingly integrated into military operations, Nexter Robotics is also looking to position itself and further expand its offerings.

First introduced at the Eurosatory 2012 exhibition, the NERVA-LG has been deployed by various organizations worldwide. Since 2017, it has been used by the US Navy SEALs and elite units like France's GIGN, the Canadian Armed Forces, and Shanghai's emergency services.

In response to the contract award, KNDS France Robotics thanked its teams for their dedication and partners for their trust. The company emphasized that this achievement reflects its commitment to providing reliable, innovative defense solutions tailored to the complex needs of military operations.

“This new order illustrates the quality and reliability of our solutions, as well as our ability to meet the specific needs of the most demanding special forces. A big thank you to our teams for their commitment and to our partners for their renewed trust,” the French company said in a statement.

Furthemore, KNDS’ modular robots serve a range of operational needs, with applications such as NERVA micro-robots for patrol duties, long-range secured communications, and sensor-to-shooter technologies. Recent developments included tests of remote-controlled bridge-laying systems, the CENTURIO robot’s role in explosive ordnance reconnaissance, and autonomous mobility trials with the AI-guided ULTRO robot.

Chinese military trials 'robot dogs' armed with machine guns learn lessons from Ukraine

Chinese troops have formed a regiment of robot-dogs armed with weapons which are programmed to respond to human voice commands.

The cyber-canines robot dogs are being used to gather intelligence, hunt enemy forces and deliver firepower with weapons mounted on their backs.

Both the US and UK are developing the use of robot dogs to work in mine clearance as well as performing reconnaissance and surveillance tasks, while China let a gun-toting robot off the leash and even a robot shark.

- **Pentagon's chilling 12-day simulation of how nuclear World War 3 would unfold**
- **Worrying nuclear map shows areas where 75% of population would die after WW3**

This year the US Army conducted tests in Saudi Arabia featuring an armed and AI-powered robot dog able to shoot down drones.

The Vision 60, developed by Ghost Robotics, is equipped with a range of high-tech features designed to enhance battlefield capabilities.

robot dog© Getty

The Chinese robot dogs carry a radio link and can be fitted with remote firing high calibre machine guns and rifles.

As unmanned platforms and artificial intelligence moves on to the battlefield, Beijing's commanders are hoping their dogs will add bite to their capability.

The robot Rexes - developed by a small team of Chinese scientists - have been programmed to respond to commands and are able to run at pace.

Chinese Robot dogs© Getty

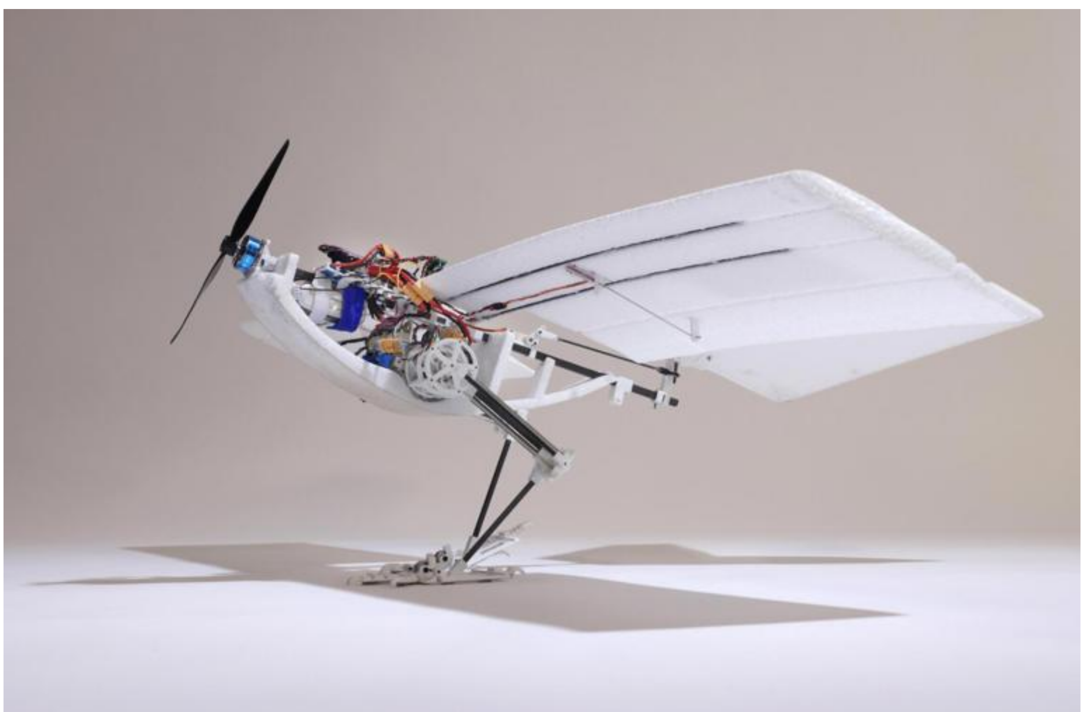
Recently unleashed at a military show in Zhuhai, the dogs were seen racing towards a target and then return to their handler after he gives them a command.

A senior source the introduction and development of AI and technology has moved at pace since the start of the Ukraine war

He added: "The potential role of these robots is vast, and the Chinese appear to be investing a lot of money in this area of technology

"We have a long way to go, but lessons learned from Ukraine show that new capabilities will be needed to counter drones in the future and that is the area the US and UK are focussed on."

Roboticists develop a bird-like robot that can jump into the air to launch itself into flight



RAVEN. Credit: EPFL/Alain Herzog with CC-BY-SA 4.0 license.

A team of roboticists at École Polytechnique Fédérale de Lausanne, working with a colleague from the University of California, has designed, built and demonstrated a bird-like robot that can launch itself into flight using spring-like legs.

The group describes their robot in a paper published in the journal *Nature*. Aimy Wissa, an aerospace engineer at Princeton University, has published a News & Views piece in the same journal issue suggesting possible ways the innovation could be used in real-world applications.

Some types of drones, such as those with rotors, can rise straight up off the ground—others that are powered with forward-facing rotors or engines that push exhaust out the back must either race along a runway or catapult to get airborne. For this new project, the research team developed a new design for getting such craft into the air—jumping using spring-like legs.

RAVEN. Credit: EPFL/Alain Herzog with CC-BY-SA 4.0 license.

The idea for springing into flight came to the researchers as they noted that crows near their office used their legs to spring into flight, which appeared to use less energy than using the wings only. That inspired them to design and build a flying robot based on the crow design.

The researchers noted that crows used their feet and legs for more than just launching into flight—they walked and ran around a lot. They also did a lot of hopping. That led the team to design a bird-like robot with legs that could be used in similar ways.

To simplify things, they chose a fixed-wing design for flight, rather than a flapping design. They also chose to use a split-V shape for the tail. An engine up front powered a single propeller.

After constructing their design, with its spring-loaded legs, the researchers conducted tests and found their little robot, which they named RAVEN (Robotic Avian-inspired Vehicle for multiple ENvironments), could walk around and hop in ways similar to crows and ravens. They also found that with some tweaking, the robot was able to jump as its rotor was spinning to ascend into the air.

The design, Wissa notes, appears to be "a viable solution to achieving multimodal locomotion for unmanned aerial vehicles."

More information: Won Dong Shin et al, Fast ground-to-air transition with avian-inspired multifunctional legs, *Nature* (2024). DOI: 10.1038/s41586-024-08228-9

Aimy A. Wissa, Bird-inspired leg enables robots to jump into flight, *Nature* (2024). DOI: 10.1038/d41586-024-03845-w

Dung beetle-inspired robot masters object rolling with adaptive leg control

Dung beetle-inspired robot masters object rolling with adaptive leg control

Inspired by the remarkable strength and efficiency of dung beetles, researchers have developed robots that mimic the beetle's unique object-rolling mechanics.

A new study explains how dung beetles roll dung balls and adjust their leg movements to navigate various terrains, providing insights for multitasking robots.

Based on ethological observations of dung beetle ball-rolling behavior, a modular neural-based loco-manipulation control is created.

The ALPHA robot, inspired by dung beetles, can walk and roll balls of various weights and types on both flat and uneven surfaces, adapting smoothly to different tasks and terrains.

"The control mechanisms can serve as guiding principles for solving sensory-motor coordination for multitasking robots," said the researchers in the study abstract.

In August, inspired by the dung beetle, scientists developed an AI sensor to measure the Milky Way's orientation accurately.

Loco-manipulation

While most legged robots are designed primarily to move around, there is a growing interest in using them for object-handling tasks as well. This combined movement and object-handling ability is called "loco-manipulation."

Some robots, like SpotMini and ANymal, use arms or grippers to manipulate objects, while others, such as the ALPHA robot, use their legs to push, lift, or carry objects. Robots that manipulate with their legs have unique advantages for handling larger, heavier objects.

Dung beetles are experts in complex object manipulation—they roll balls of various weights across different terrains, which allows them to transport objects nearly twice their size. Their coordination involves pushing on the ground with their front legs and rolling the ball with their middle and hind legs.

According to researchers, while this efficient technique could inspire new robot designs, the beetles' exact motor patterns, and neural controls for handling different ball weights and surfaces remain a mystery. Translating these natural strategies into robotics could improve future-legged robots' ability to handle diverse objects.

Adaptive robot control

The study explored how dung beetles' neural systems help them adapt their movements to roll different ball types and weights across various terrains.

Researchers designed a neural control system for a robot modeled after dung beetles (named ALPHA) based on four key ball-rolling principles from beetle behavior. The system includes a rhythm generator for movement, an orientation control for balance, and adaptations like flexible legs for better grip and terrain flexibility.

Using this setup, ALPHA can handle and roll balls twice its leg length across flat and uneven surfaces, achieving rolling speeds of 10–20 cm per second. The robot adjusts its posture dynamically, stabilizing and adapting to various conditions—whether soft, rigid, light, or heavy balls.

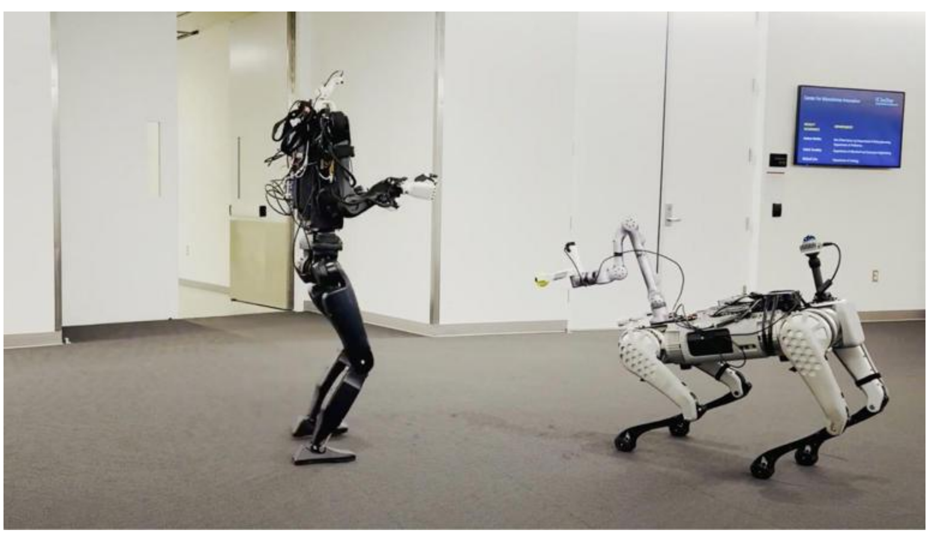
The experiment showed that ALPHA's neural-based control system allowed it to roll both soft and rigid balls across flat and uneven terrain with success rates of up to 80 percent. Adding compliant fin-ray tarsi and soft material to its legs improved stability and grip, especially on challenging terrain.

On flat surfaces, ALPHA achieved a consistent 100 percent success rate with the softball. The ROC module's real-time adjustments enabled adaptive movement, preventing slipping and improving control, though occasionally limiting speed.

According to researchers, the bio-inspired approach offers new insights into complex, multi-functional robot designs, especially for hexapod and quadruped robots, potentially enhancing their capabilities for both movement and large-object handling.

The details of the research were published in the journal *Advanced Sciences*.

WildLMa teaches robots new tricks to do household chores, handle 'unseen' situations



WildLMa teaches robots new tricks to do household chores, handle 'unseen' situations

Robotics research is steadily advancing towards a future where robots can be integrated into daily human life, can do mundane tasks, and free up people's time for more enjoyable activities.

While it may sound like a distant dream, researchers at UC San Diego are bringing this vision closer to reality with their groundbreaking work on WildLMa, a new framework designed to enhance the capabilities of quadruped robots.

"Quadruped robots with manipulators hold promise for extending the workspace and enabling robust locomotion, but existing results do not investigate such a capability," said the researchers in a paper on the arXiv preprint server.

WildLMa focuses on improving the robots' ability to perform "loco-manipulation" tasks, which involve manipulating objects while moving around in their environment. It aims to enable robots to not only navigate homes but also pick up clutter, fetch items, and even put away groceries.

"Consider a scenario where a mobile robot is deployed out-of-box at a family house. The robot is tasked with daily chores including collecting the trash around the house and grabbing something for humans," added the research team.

However, this requires a high level of coordination and adaptability.

Challenges in real-world settings

Traditional methods for training robots often rely on imitation learning, where robots learn by observing and mimicking human demonstrations. While this approach has shown promise in simulated environments, it often falls short when robots are deployed in the "unseen" real world.

The complexity and unpredictability of real-world environments require robots to generalize their learned skills and adapt to new situations. "WildLMa designs three components to address challenges for in-the-wild mobile manipulation," asserted the team.

First, it utilizes a VR-based teleoperation system, allowing human operators to control the robot's movements using pre-trained algorithms. This simplifies the process of collecting expert demonstration data, as humans can intuitively guide the robot through various tasks.

Second, WildLMa leverages Large Language Models (LLMs) to break down complex tasks into smaller, more manageable steps. This is akin to how humans approach a problem by dividing it into sub-tasks. By providing the robot with a clear sequence of actions, LLMs enable it to execute long, multi-step tasks efficiently and intuitively.

Third, the framework incorporates attention mechanisms, which allow the robot to focus on target objects while performing tasks. This is crucial for ensuring that the robot remains attentive to its surroundings and avoids distractions.

Training and experiments

The researchers have demonstrated the effectiveness of WildLMa in a series of real-world experiments.

"Besides extensive quantitative evaluation, we qualitatively demonstrate practical robot applications, such as cleaning up trash in university hallways or outdoor terrains, operating articulated objects, and rearranging items on a bookshelf," highlighted the team.

These experiments showcase the potential of WildLMa to enable robots to perform useful tasks in our everyday lives.

"Our experiments include 20 training sequences with variations in robot positioning, lighting, and object placement in both the training and testing time," concluded the researchers.

"WildLMa successfully learns generalizable skills from a limited number of demonstrations to achieve better success rates for long-horizon execution."

The development of WildLMa represents a significant step forward in the field of robotics. By enhancing the loco-manipulation skills of quadruped robots, this framework paves the way for the creation of more versatile and capable robots that can assist humans in various settings.

Robot watches how-to videos and becomes an expert surgeon

BALTIMORE — How-to videos are great for humans looking to pick up some quick skills. Now, it turns out they're also great for robots looking to become amazing surgeons. In a groundbreaking step towards robotic autonomy, researchers have developed an AI system that can carry out complex surgeries with the same precision as seasoned human doctors. The secret? Letting the robots learn by watching the pros do it first.

Traditionally, programming robots to perform even the simplest surgical maneuvers has required painstakingly hand-coding each individual movement. Now, the team from Johns Hopkins University, led by Axel Krieger, has cracked the code using a revolutionary technique called imitation learning.

"It's really magical to have this model and all we do is feed it camera input and it can predict the robotic movements needed for surgery," Krieger says in a media release. "We believe this marks a significant step forward toward a new frontier in medical robotics."

Video credit: Johns Hopkins University

The researchers trained their model on a trove of footage recorded by wrist-mounted cameras on the popular da Vinci Surgical System robots. With nearly 7,000 of these robots deployed worldwide, and over 50,000 surgeons trained on the platform, the team had a vast archive of surgical procedures to draw from.

"All we need is image input and then this AI system finds the right action," explains lead author Ji Woong "Brian" Kim. "We find that even with a few hundred demos the model is able to learn the procedure and generalize new environments it hasn't encountered."

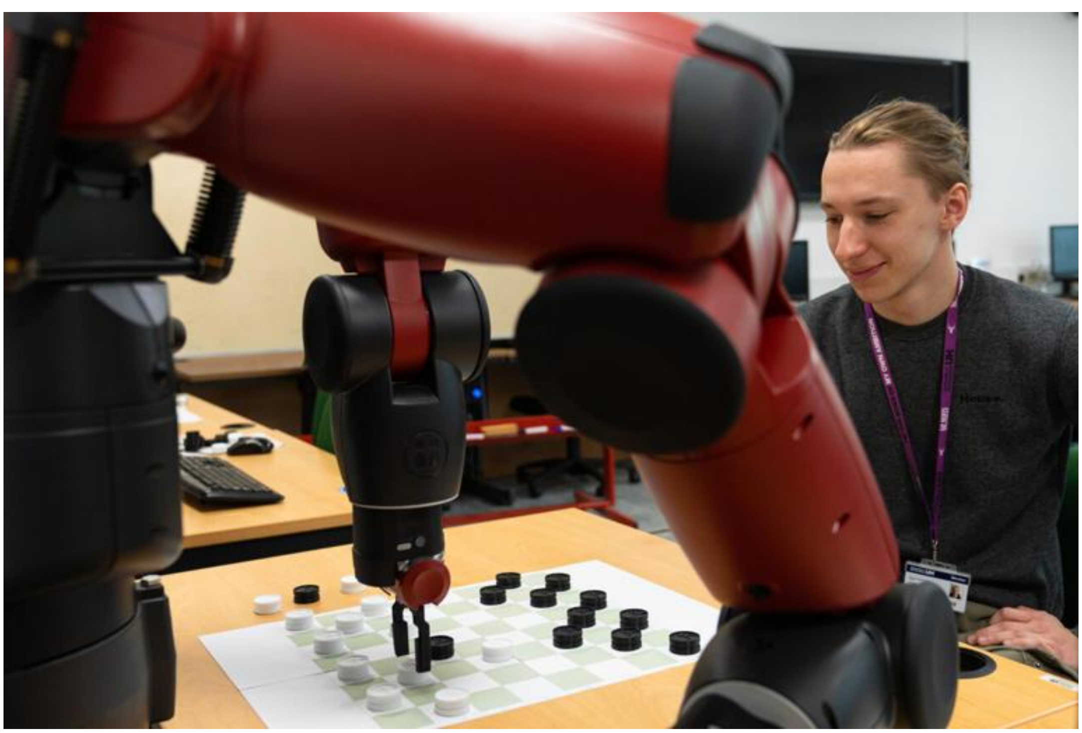
The model was able to master three fundamental surgical tasks: needle manipulation, tissue lifting, and suturing. In each case, the robotic performance was on par with human doctors.

“Here the model is so good learning things we haven’t taught it,” Krieger says. “Like if it drops the needle, it will automatically pick it up and continue. This isn’t something I taught it do.”

This breakthrough, presented at the Conference on Robot Learning in Munich, could pave the way for a future where robots can autonomously perform complex surgeries, reducing medical errors and achieving unprecedented precision.

“What is new here is we only have to collect imitation learning of different procedures, and we can train a robot to learn it in a couple days,” Krieger explains. “It allows us to accelerate to the goal of autonomy while reducing medical errors and achieving more accurate surgery.”

With this powerful imitation learning approach, the researchers are already working to train robots for full surgical procedures, not just individual tasks. The implications for the future of robotic medicine are nothing short of revolutionary.



Robots play Chess against University staff and students. Credit: University of Hertfordshire

Researchers from the University of Hertfordshire have developed a new algorithm that will allow robots to function more intuitively—that is, make decisions using their environment for guidance.

The principle is that, through the algorithm, the robot agent creates its own goals.

For the first time, the algorithm unifies different goal-setting approaches under one concept which is tied directly to physics, and it furthermore makes this computation transparent so that others can study and adopt it.

The principle of the algorithm is related to the famous chaos theory, because the method makes the agent "master of the chaos of the system's dynamics."

The study has been published in the journal *PRX Life*. Herts researchers explored robot "motivation models" that mimic the decision-making processes of humans and animals, even in the absence of clear reward signals.

The study introduces artificial intelligence (AI) formulas that compute a way for a robot to decide future actions without direct instructions or human input.

Daniel Polani, Professor of Computer Science and senior author explains, "In an applied sense, what this could mean, for example, is getting a robot to play and manipulate objects on its own without being told to do so.

"It could enhance the way robots learn to interact both with humans and with other robots by encouraging more 'natural' behaviors and interactions.

"This has further applications—such as the survivability behavior of semiautonomous robots placed in situations where they are unreachable by a human operator, such as in subterranean or interplanetary locations."

In humans and animals, one theory assumes the existence of an "intrinsic motivation," where behaviors are driven only by the interaction between the being and its environment rather than by specific learned rewards, such as food.

This paper successfully translates that "intrinsic motivation" theory into one that can be used by robotic agents.

Professor Polani adds, "This work is exciting because we can now implement a mechanism, similarly to those helping humans and animals solve new problems without prior experience, in robots.

"We expect that we can build on this work to develop more human-like robots in the future with more intuitive processes. It opens up a huge opportunity for more sophisticated robots with similar decision processes to us."

The theory underlying this paper, called "empowerment maximization," has been developed at Herts for many years. It suggests that by increasing the range of future outcomes, a robot will have better options also in the longer future. Importantly, this method replaces and thus possibly obviates traditional reward systems (e.g. food signals).

While empowerment maximization has shown promise, it is not yet fully understood or widely applied. Most studies used to rely on simulations, while meticulously calculating the necessary information for complex systems and the theory remains challenging.

However, this latest innovative research aims to explain why empowerment-based motivations can create behaviors similar to those of living organisms, potentially leading to more intrinsically motivated robots; and it additionally offers a significantly improved way to compute these motivations.

Professor Polani says the next steps are to use this breakthrough algorithm to allow robots to discover more about the world, developing direct learning and identifying and honing new skills that would drive their value in real-world scenarios.

More information: Stas Tiomkin et al, Intrinsic Motivation in Dynamical Control Systems, *PRX Life* (2024). DOI: 10.1103/PRXLife.2.033009

Dresden Researchers Enable Robots to Sense and Feel

[To expand the capabilities of robots, scientists in Dresden have developed robotic hands with advanced sensing abilities](#). Inspired by nature, these robotic hands use sensor integration and 3D printing to replicate the delicate touch of a human hand. This breakthrough could pave the way for robots that harvest crops, assemble products, or explore remote terrains with greater dexterity and control.

By John Adams

Nature-Inspired Robotics for Enhanced Dexterity

Dresden Researchers Enable Robots to Sense and Feel© Provided by Ever-Growing

Researchers from Dresden's Fraunhofer Institute for Material and Beam Technology (IWS) have developed robotic grippers that "feel" by mimicking natural systems. Using a combination of 3D and dispensing printing, they've engineered grippers equipped with sensors that gauge force, allowing robots to grip objects with precision. These enhanced robots could soon be used in agriculture to pick delicate produce or in planetary exploration to handle unknown objects carefully. Projects like "BioGrip" and "Nature4Nature" aim to replicate biological principles to build robotic grippers that act similarly to human hands.

Borrowing Abilities from Aquatic Life

In designing these sensitive grippers, scientists drew inspiration from fish, whose fins naturally respond to pressure by moving inward rather than away from it. This adaptive response, known as the “Finray effect,” allows fish to move more efficiently by creating an opposing force to external pressure. Applying this principle, engineers have designed grippers that use sensors and Finray-inspired movement to hold objects securely without exerting damaging force. This technology was developed and tested extensively through the BioGrip project between mid-2021 and early 2023.

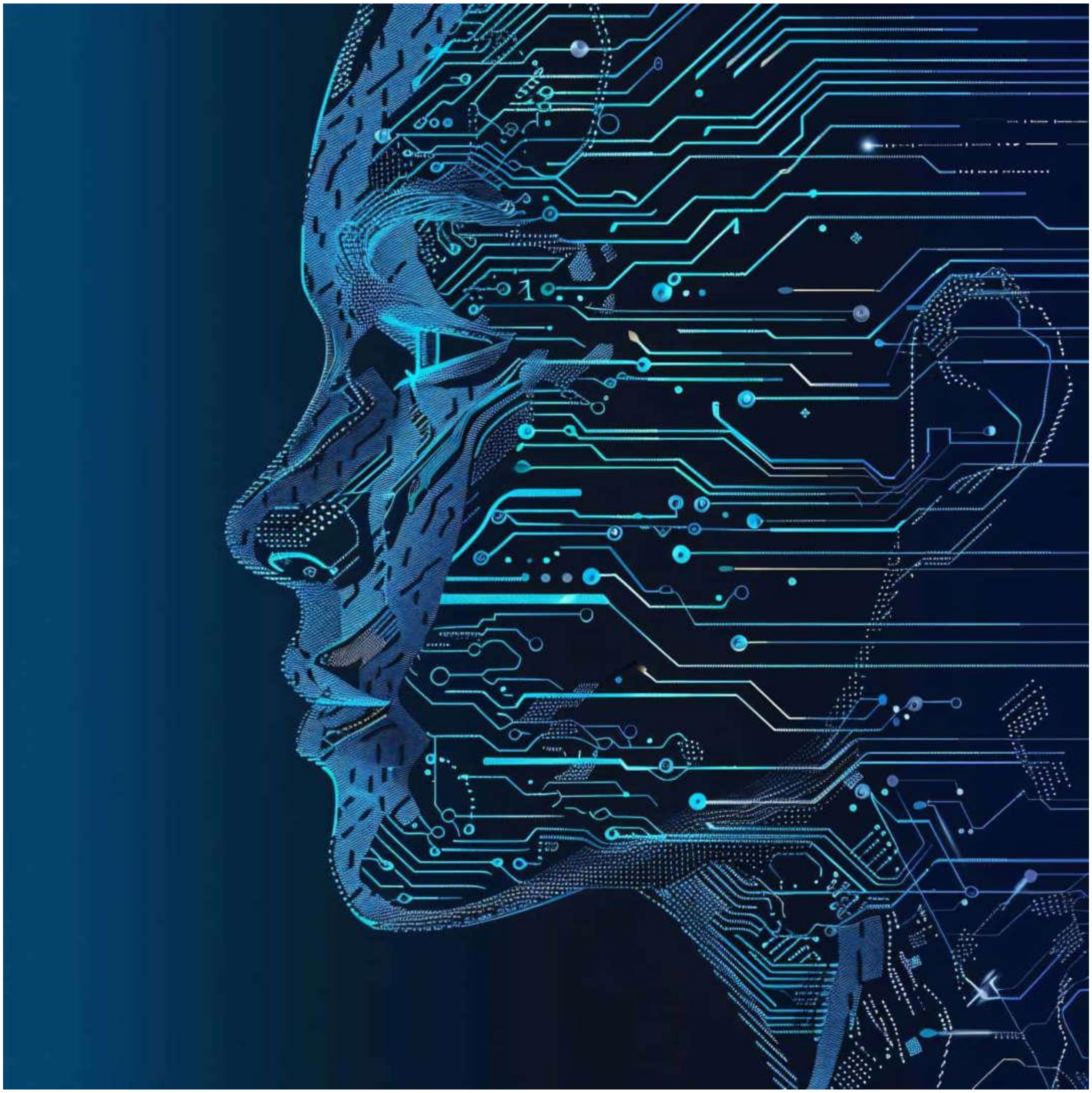
Advanced Sensors Mimic Human Touch

The team’s work centers on sensors that enable robots to recognize exactly how much pressure is needed for different objects, preventing damage to fragile items. With this technology, robotic grippers can “sense” texture and firmness, adjusting their grasp accordingly. These advancements open up applications in agriculture, where robotic harvesters could gently pick fruit, and in underwater exploration, where robotic arms can handle sensitive marine samples. The combination of biological principles and modern technology is transforming robot interactions with their environment.

The Future of Responsive Robotic Applications

As robotic technology advances, the use of nature-inspired designs could revolutionize machine function in numerous fields. Responsive grippers are being tested across different industries, from food processing to space exploration, enhancing the potential of robots to operate autonomously. Engineers hope that continued advancements in bionic technology will create machines capable of performing increasingly complex tasks with minimal human intervention. This fusion of sensor technology with biological inspiration marks a significant step toward more adaptable and self-sufficient robotic systems.

This latest research highlights the promise of biologically inspired technology to transform robotics, offering an exciting glimpse into future applications.



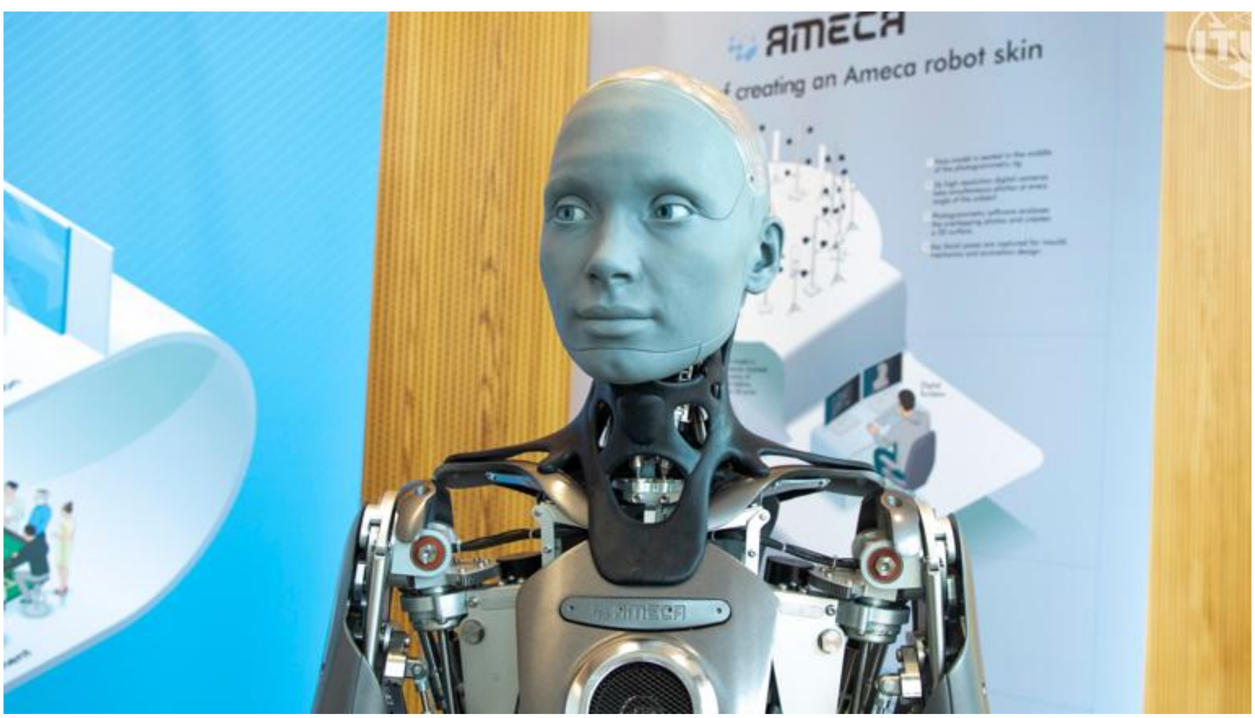
AMECA, Atlas, Optimus: Top 10 insane humanoid robots to watch out for in 2025

Our fascination with creating machines in our own image has led us to remarkable achievements. We have managed to push the boundaries of artificial intelligence and robotics to the point where today's humanoid robots not only mimic but also enhance human interaction.

From Hephaestus's mythical automaton servants to icons like C-3PO and The Terminator, humanoid robots, once confined in mythology and fiction, now walk among us.

These mechanized versions of ourselves assist us in surgeries, speeding along assembly lines, and even exploring outer space. Here, we have listed the most advanced humanoid robots of 2024, whose real-life capabilities are as extraordinary as the tales that once imagined them.

AMECA



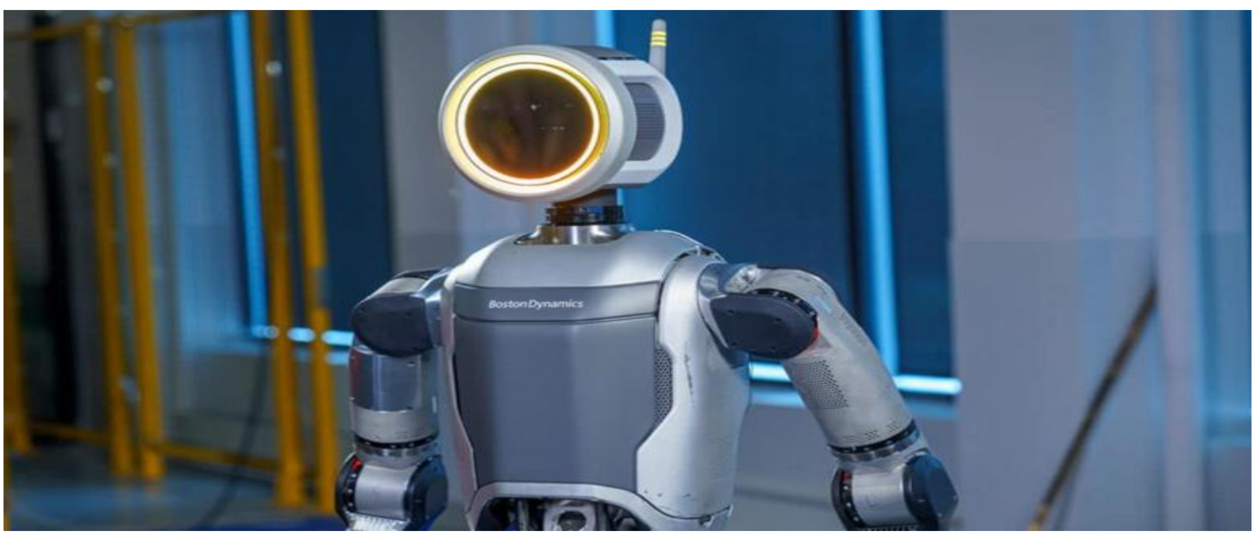
When you search for the "world's most advanced humanoid," most paths lead to AMECA by Engineered Arts, and it's easy to see why. AMECA is engineered to be modular and upgradeable in both hardware and software, designed with a gender-neutral and non-threatening appearance to facilitate comfortable human-robot interactions.

It utilizes embedded microphones, binocular eye-mounted cameras, a chest camera, and facial recognition software. It is an excellent platform for further developing robotics technologies focusing on human-robot interaction. Although AMECA cannot walk yet, it is designed with the potential for mobility in the future.

AMeca's cognitive capabilities are amplified through integration with OpenAI's GPT-3 and GPT-4 language models, enabling it to understand and respond to questions, tell jokes, mimic the voices of celebrities or famous TV characters, dance, and hold engaging conversations.

What sets AMECA apart is its incredibly realistic facial expressions and movements, with 27 actuators controlling minute details such as lip and eyebrow movements and motorized arms, fingers, and neck, totaling 61 degrees of freedom. These features allow AMECA to communicate naturally and expressively, distinct from other robots.

Atlas



Atlas, developed by Boston Dynamics, is renowned for its athleticism, often showcased through its impressive dance moves and backflips. This robot was initially created as a research project for the U.S. Defense Advanced Research Projects Agency (DARPA) in 2009. In a significant development, the hydraulic Atlas (HD Atlas) was retired in April of 2024, succeeded by a new, fully electric version announced the following day.

The transition from hydraulic to electric systems marks a leap towards greater efficiency and environmental sustainability. Atlas is built upon decades of robotics research, featuring a custom battery and a highly compact former hydraulic system, now re-engineered for electric operation.

Its advanced control algorithms allow Atlas to plan and execute complex movements, considering environmental factors, and achieve speeds up to 2.5 m/s. Composed of titanium and aluminum with 3D printed parts, Atlas possesses a strength-to-weight ratio that facilitates its dynamic maneuvers.

The robot stands 1.5 meters tall, weighs 89 kg, and includes 28 joints that support agile and diverse locomotion. Atlas is equipped with advanced infrared stereo and depth sensors to create detailed environmental point clouds, using a blend of vision, force, and proprioceptive sensors to adapt to environmental changes.

Optimus

Optimus, also known as Tesla Bot and named after the Transformers character, is a general-purpose robotic humanoid initially announced during Tesla's Artificial Intelligence Day on August 19, 2021. A prototype was showcased in 2022, and by December 2023, Tesla introduced Optimus Generation 2, which featured a slimmer figure and improved hands and movements.

In 2024, this new robot was demonstrated performing various tasks at a Tesla factory, highlighting its enhanced capabilities, being 10 kg lighter and faster than its predecessor.

In June 2024, Elon Musk announced plans for Optimus to enter limited production in 2025, with over 1,000 units intended for use in Tesla facilities and potential broader production for other companies by 2026. Priced at an estimated US$30,000, Musk envisions Optimus performing a wide range of everyday tasks inside and outside the home.

The robot utilizes a bipedal walking system designed for balance and stability, featuring pressure sensors on its feet to adjust its stance in real-time. It includes multiple cameras in its "face" for object detection, depth gauging, and spatial processing, alongside an onboard neural network processing system for learning and adaptation.

Optimus can respond to voice commands and understands basic conversational contexts. It is powered by a 2.3 kWh battery pack, similar to Tesla's electric vehicles. It includes a proprietary battery management system, allowing it to move at speeds up to 5 mph (8 km/h) and carry loads up to 45 pounds (20 kg).

Figure 02

Figure AI introduced its initial prototype, Figure 01, in 2022. A bipedal robot aimed at manual labor tasks in logistics and warehousing. On August 6, 2024, the company unveiled Figure 02, the next generation of its humanoid robot. This version sports a sleeker, slimmer design with integrated cabling in its limbs, which Figure AI claims to be the world's first commercially viable autonomous humanoid robot.

The new robot features a 50% increase in battery capacity over its predecessor. It is equipped with 6 RGB cameras and an onboard vision language model. The computing power is significantly enhanced, powered by NVIDIA RTX GPU-based modules, offering three times the inference capabilities of the earlier model.

Additionally, Figure 02 includes microphones and speakers paired with a custom AI model developed in collaboration with OpenAI, enhancing its conversational abilities with humans. Its redesigned five-fingered hands boast 16 degrees of freedom, enabling it to carry objects weighing up to 25 kg. Figure 02 is currently being tested at a BMW plant in South Carolina to gather training data for further AI model development.

DIGIT

Digit is a humanoid robot designed by Agility Robotics with a distinctive inwardly curved leg design that enhances mobility, enabling it to move dynamically through complex environments. This unique structure is complemented by elegant limbs and a torso packed with advanced sensors and computing power, making Digit well-suited for navigating and performing tasks in places like warehouses.

Released in 2023, Digit represents a significant advancement in robotic capabilities, underscored by the announcement of Agility Robotics' first humanoid robotics factory, RoboFab, which produces up to 10,000 robots annually.

Digit is constructed from aluminum, thermoformed polycarbonate, and carbon fiber composite components, ensuring both lightness and strength. It is equipped with a range of sensors, including Lidar, four Intel RealSense depth cameras, and MEMS IMU, alongside absolute and incremental encoders that enhance its proprioception.

The robot features brushless DC motors with custom-designed transmissions and has 16 independent joints. These joints allow Digity to move its legs and arms in 10 different ways, possessing four degrees of freedom and coming with grippers in 6 different ways.

The robot's computational needs are handled by two Intel i7 multi-thread CPUs, with a payload bay available for additional computers like an Intel NUC or Nvidia Jetson, which can be used for enhancing perception or machine learning tasks.

Digit operates on a Linux-based real-time operating system for its main control computer, with high-level planning and perception managed on a secondary computer. It is powered by a custom 1.2-kWh lithium-polymer battery pack, balancing power efficiency with robust operational capabilities.

Apollo

Apollo, developed by Apptronik, is another groundbreaking humanoid robot benefiting from the company's extensive experience in robotics, including their work on NASA's Valkyrie robot. Apollo is tailored for mass manufacturability and is designed to function in collaborative environments with high payloads and safety standards.

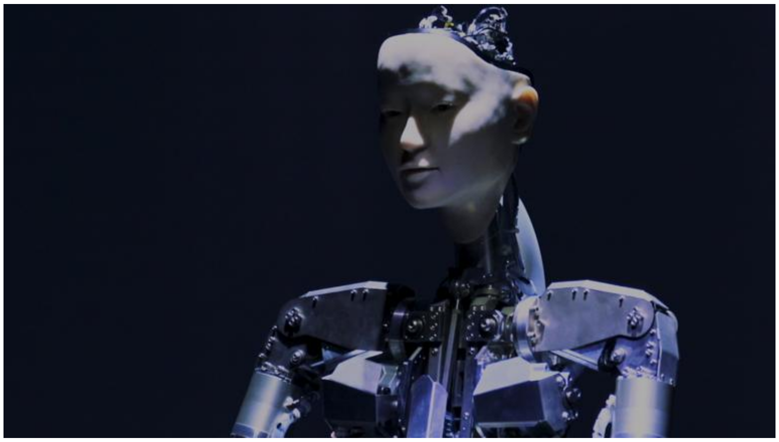
Weighing approximately 72.6 kilograms and capable of operating up to 4 hours on a single battery pack, Apollo is built to match the size and capabilities of a human, making it suitable for various tasks that require human-like attributes.

Apollo's design allows it to carry payloads of up to 25 kilograms, emphasizing its ability to perform substantial lifting and carrying tasks. The robot is exceptionally versatile, with a modular design that can be mounted on any mobility platform, whether stationary or fully mobile, with legs.

It features LEDs in the head, mouth, and chest to communicate its status, and it is equipped with hot-swappable battery packs that each offer four hours of runtime, allowing for continuous operation with simple battery changes rather than requiring downtime for recharging.

Additionally, Apollo incorporates an Advanced Force Control Architecture and defines safety zones for enhanced operational safety. It can be controlled through intuitive software accessible on any device, simplifying human-robot interaction. Mercedes-Benz has recognized Apollo's utility and is integrating these robots into their factories to assist with physically intensive and low-skill tasks, showcasing Apollo's industrial applicability and efficiency.

ALTER 3



ALTER 3 stands out in the list of top humanoid robots for its unique blend of AI and musical talent, notably demonstrated through its ability to conduct orchestras. Developed by Osaka University and Mixi Corporation, this humanoid robot has been used in various experimental settings, including conducting orchestras, participating in theatrical performances, and exploring the intersection of robotics and the arts.

ALTER 3's design features a highly expressive face capable of displaying a wide range of emotions, such as smiling, frowning, and even singing, enhancing its interaction with human audiences.

The robot's body combines prosthetic skin on its face, neck, and arms up to the elbows, with other parts remaining as exposed machinery to evoke a sense of the mechanical nature of life. This design choice highlights the robot's internal mechanisms and sparks discussions about the nature of humanity and the potential of artificial intelligence.

ALTER 3 utilizes a combination of pneumatic and servo-based actuators, controlled by 42 actuators and a central pattern generator (CPG) integrated with a neural network, allowing for fluid and lifelike movements.

The robot is equipped with optical and distance sensors for autonomous movement, and its sensors and microphones feed into an AI system that enables it to respond dynamically to its environment. The development of ALTER 3 aims to probe fundamental questions about whether robots can obtain a sense of life and what life itself may mean.

Unitree G1

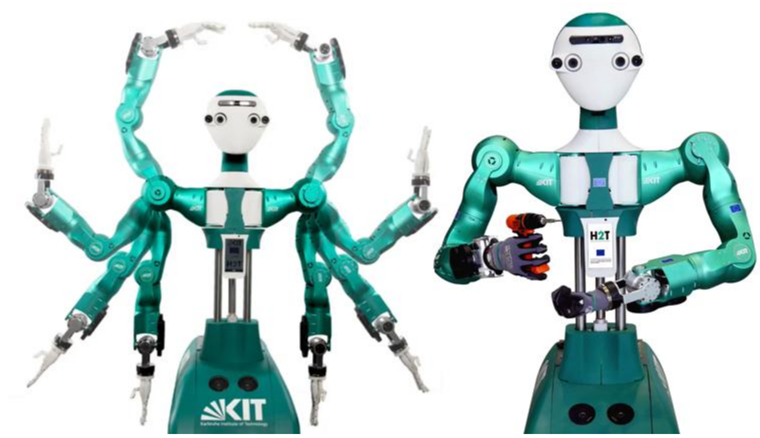
Unitree G1 is recognized for its exceptional flexibility and affordability, making it a standout choice for robotics research and development. The robot is designed to facilitate the exploration of advanced locomotion and manipulation techniques, capable of performing a standing long jump of up to 1.4 meters—possibly the longest jump ever achieved by a humanoid robot of its size.

The G1 robot is equipped with a dexterous 3-fingered hand that allows for precise manipulation, supported by a maximum joint torque of 120 Nm. It boasts 43 degrees of freedom, enabling complex movements, and moves at a speed of 2 m/s. Sensory and communication enhancements include 3D LIDAR with a LIVOX MID360 for 360° detection, an Intel RealSense D435i depth camera, and a microphone array with noise and echo cancellation capabilities.

Its battery and power systems feature an extra-large quick-release battery, supporting about two hours of battery life, and the robot's design includes hollow joint wiring, eliminating the need for external cables. Both G1 and G1 EDU models are further equipped with a high-performance 8-core CPU, depth camera, 3D LiDAR, four-microphone array, and connectivity options like WiFi 6 and Bluetooth 5.2.

Accessories include a smart battery with quick release (9000mAh), a 54V 5A charger, and a manual controller. The G1 comes with an 8-month warranty, while the G1 EDU offers a 1-year warranty, with pricing for the G1 starting at US $16,000.

ARMAR-6



Karlsruhe Institute of Technology

ARMAR-6, part of the ARMAR series of humanoid robots developed at the Karlsruhe Institute of Technology, represents a lineage of robots that dates back to 2000 with ARMAR-1, focusing initially on basic locomotion and manipulation. Successive models such as ARMAR-2, ARMAR-3a, and ARMAR-3b (developed between 2004 and 2007) have seen progressive improvements, enhancing capabilities in interaction and more complex tasks.

ARMAR-6, a collaborative humanoid assistant designed for industrial environments, embodies these advancements.

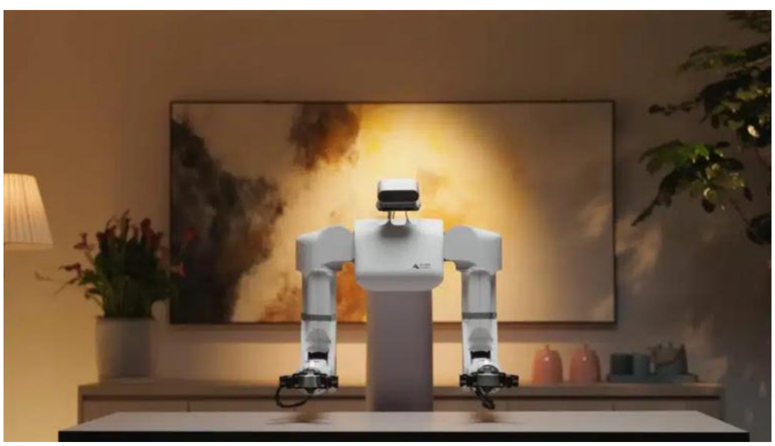
ARMAR-6 features a human-like torso and two arms mounted on a wheeled base, enabling it to navigate industrial settings and utilize tools designed for humans, like power drills and hammers. This robot has four computers in its mobile base, providing substantial computational power for control, image processing, interaction algorithms, and implementing machine learning and artificial intelligence through its ArmarX software architecture.

Its joints are powered by specially developed sensor-actuator-controller units that allow precise and force-controlled movements, including continuous joint rotation facilitated by slip rings.

The robot boasts 27 degrees of freedom and can lift to 10 kg with an arm fully stretched out, achieving a maximum lifting capacity of 14 kg at average distances. Standing at 192 cm with an arm span of 310 cm, ARMAR-6 operates at a working height range from 0 cm to 240 cm and weighs 160 kg without batteries.

Its sensors include position, IMUs, torque, and temperature sensors across its joints, supplemented by 6D force-torque sensors for interaction and laser scanners for navigation. Two stereo camera systems, a depth camera, and microphones enhance perception capabilities. ARMAR-6 runs on an EtherCAT bus system, linking its multiple high-end PCs and GPU, ensuring robust autonomous operations facilitated by a powerful battery system.

Astribot S1



Astribot

Astribot S1, described as an 'all-purpose' home robot, is specifically designed for household tasks such as cooking, folding clothes, and operating a vacuum cleaner. Unlike traditional humanoid robots with legs, the Astribot S1 features motorized wheels and a flexible lower body that can bend in the middle, supporting its tasks around the home with impressive agility and mobility.

Standing approximately 5 feet 8 inches tall, Astribot S1 has a slender, sleek white design. It boasts a payload capacity of 10 kg per arm and 7 degrees of freedom per arm, allowing for a range of motion that rivals a human limb. The robot's arms are equipped with touch sensors for safe interaction with objects and people. Instead of a typical humanoid hand, it ends in a sensor-packing dual-digit gripper, enhancing its capability for varied and precise tasks.

Astribot S1's agility and dexterity are notable, with a top speed of 10 meters per second, faster than the average adult human. It can learn new tasks through imitation learning, a feature showcased in various online demonstrations where the robot performs activities like martial arts, making pancakes, and pouring drinks. The robot was announced to be commercially available in 2024, although specific details about its hardware specs or AI learning methods remain undisclosed by the company.

Humanoid robots moving forward

As we conclude our exploration of the most remarkable humanoid robots of 2024, it's clear that the field of robotics continues to break boundaries and challenge our expectations. In addition to the key players discussed numerous other humanoid robots are making strides in specialized areas.

These include Nadine, who provides valuable social interaction; Robonaut 2 with its space-oriented tasks; Sophia for her engaging discussions; Pepper's role in service industries; and NAO's contributions to educational settings. Recent advancements in achieving a human-like gait in the SEO1 humanoid also hint at many other pioneering projects.

While we've highlighted some key players, countless other advancements are being made in labs and institutions around the globe, each promising to further revolutionize how we interact with machines.

Watch how Tesla's humanoid robot recovers from a stumble

Tesla has released a video (below) of its Optimus humanoid robot out for a leisurely stroll. The 38-second footage shows off the robot's ability to handle soft, uneven ground, and for most of the time the bipedal bot looks pretty comfortable as it walks about.

The most impressive part, however, comes at the end of the video when Optimus recovers rather gracefully from an awkward slip as it descends a small but steep slope. To recover in this way requires a lot of complex and lightning-fast computing power, so the robot clearly does well to stay upright.

In an online post sharing the video, Tesla boss Elon Musk said, "Optimus can now walk on highly variable ground using neural nets to control its electric limbs."

Milan Kovac, vice president at Optimus, elaborated in a post of his own, noting that Optimus is seen walking on mulched ground where he once slipped himself.

Kovac said: "What's really crazy here is that for these [walks], Optimus is actually blind," adding that the robot is maintaining its balance without any cameras to guide it, relying instead on built-in sensors integrated with its onboard computer.

The executive said that to enable Optimus to plan ahead as it walks, his team intends to incorporate computer vision, a sophisticated system that will enable the robot to perceive and interact with its environment. They also want to improve the robot's walking style to make it look more natural, and in cases where a fall is unavoidable, it wants to design a safe way for it to topple over to minimize damage.

Looking at videos of Boston Dynamics' bipedal Atlas robot during its development, we can see that it was walking in a similar way to Optimus back in 2016. A year later it was performing backflips, and not long after that it was able to jog. We're looking forward to seeing Optimus's hopefully rapid progression over the next couple of years.

Musk unveiled Optimus in 2021. At the launch event, Tesla didn't have a working prototype ready so instead it hauled onto stage someone in a skintight bodysuit. It's fair to say that the robot has come a long way since then.

The Tesla chief said we could see "thousands" of the robots working alongside human staff at Tesla factories as early as next year, taking care of "dangerous, repetitive, [and] boring tasks." But Musk's target dates are known to slip, so don't be surprised if it doesn't happen.

Plans for a commercial launch are also in the pipeline, but not until 2026 at the earliest. Costing up to a whopping $30,000, Musk claims that Optimus could one day function as a household helper capable of various tasks such as "babysit your kid, walk your dog, mow your lawn, get the groceries, just be your friend, serve drinks."

Video Shows Robot Welding SpaceX Starship

Footage recently shared by NASASpaceflight shows a massive robotic arm appearing to weld one of the company's Starship nosecones.

A Cure for Weldness

SpaceX is pulling out all the stops in preparation for the upcoming test launches of its gigantic Starship spacecraft next year.

Footage shared by *NASASpaceflight* shows a large robotic arm appearing to weld one of the company's Starship nosecones inside of its "Starfactory," a massive facility at the company's "Starbase" launch complex in South Texas.

According to documents obtained by *The Launch Pad Network* last month, SpaceX is targeting no earlier than January 11 for its upcoming seventh Starship test.

The launch is expected to involve a new generation of Starship prototypes dubbed "Block 2," the first of which will be "Ship 33." (It's unclear whether the nosecone in the latest footage belongs to it or a different Block 2 Starship.)

The prototype will feature a new forward flap design, a new heatshield layout, increased propellant capacity, and possibly even more thrust than its predecessors, among other changes.

In other words, SpaceX is making some considerable changes to the design of its Moonbound rocket, which could raise the stakes for the upcoming test launch next month.

Acid Test

According to *NASASpaceflight*, Ship 33 completed early cryogenic testing in late October.

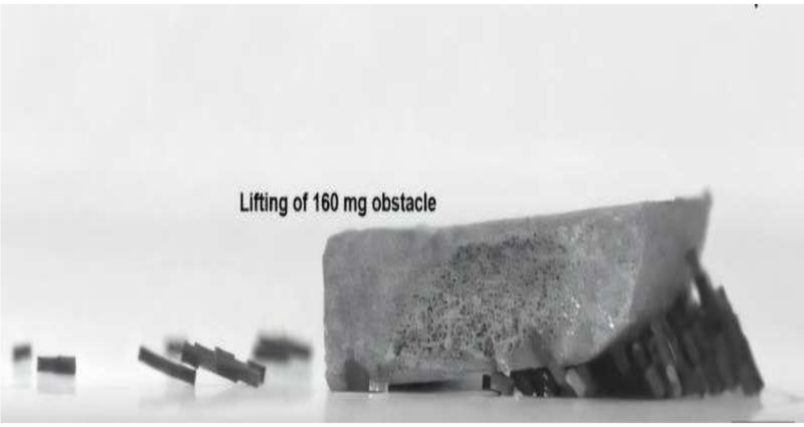
But whether it survives its upcoming test flight unscathed remains unclear. During the previous two launches, SpaceX's Starship spacecraft splashed down in the ocean after experiencing scorching and metal-melting temperatures during reentry.

To SpaceX CEO Elon Musk, getting to the point of being able to launch again shortly after landing will be the real litmus test for an extremely ambitious, heavy-lift launch platform that NASA is still hoping to use for its first — and recently delayed — human landing on the Moon since the 1970s.

"The biggest technology challenge remaining for Starship is a fully & immediately reusable heat shield," he tweeted last month. "Being able to land the ship, refill propellant and launch right away with no refurbishment or laborious inspection. That is the acid test."

DECEMBER 18, 2024

Watch 'ant-like' robot swarms conquer obstacles and transport heavy loads



Robots lifting and object. Credit: Device/Yang and Won et al.

Scientists in South Korea have developed swarms of tiny magnetic robots that work together like ants to achieve Herculean feats, including traversing and picking up objects many times their size.

The findings, published December 18 in *Device*, suggest that these microrobot swarms—operating under a rotating magnetic field—could be used to take on difficult tasks in challenging environments that individual robots would struggle to handle, such as offering a minimally invasive treatment for clogged arteries and precisely guiding organisms.

"The high adaptability of microrobot swarms to their surroundings and high autonomy level in swarm control were surprising," says author Jeong Jae Wie of the Department of Organic and Nano Engineering at Hanyang University in Seoul, South Korea.

Wie and colleagues tested how well microrobot swarms with different assembly configurations performed at a variety of tasks. They found that swarms with high aspect ratio assembly could climb an obstacle five times higher than the body length of a single microrobot and hurl themselves, one by one, over an obstacle.

Robots traversing lifting and guiding objects. Credit: Device/Yang and Won et al.

A large swarm of 1,000 microrobots with high packing density formed a raft that floated on water and wrapped itself around a pill that weighed 2,000 times more than each individual robot, enabling the swarm to transport the drug through the liquid.

On dry land, a robot swarm managed to transport cargo 350 times heavier than each individual, while another microrobot swarm was able to unclog tubes that resembled blocked blood vessels. Finally, through spinning and orbital dragging motions, Wie's team developed a system through which robot swarms could guide the motions of small organisms.

Scientists have become increasingly interested in studying how swarms of robots can collectively achieve goals, inspired by the way ants band together to bridge a gap in a path or huddle in the shape of a raft to survive floods.

Similarly, working together makes robots more resistant to failure—even if some members of the group fall short of the goal, the rest keep performing their programmed motions until enough of them eventually succeed.

Guiding an ant and more. Credit: Device/Yang and Won et al.
"Previous swarm robotics research has focused on spherical robots, which come together through point-to-point contact," says Wie. In this study, the researchers designed a swarm made up of cube-shaped microrobots, which share stronger magnetic attractions since larger surface areas—entire faces of each cube—can come into contact.

Each microrobot stands 600 micrometers tall and consists of an epoxy body embedded with particles of ferromagnetic neodymium-iron-boron (NdFeB), which enables it to respond to magnetic fields and interact with other microrobots. By powering the robots with a magnetic field generated by rotating two connected magnets, the swarm can self-assemble.

The researchers programmed the robots to come together in different configurations by varying the angle at which the robots were magnetized.

"We developed a cost-effective mass production method using onsite replica molding and magnetization, ensuring uniform geometry and magnetization profiles for consistent performance," says Wie.

"While the study's results are promising, the swarms will need higher levels of autonomy before they will be ready for real-world applications," says Wie.

"The magnetic microrobot swarms require external magnetic control and lack the ability to autonomously navigate complex or confined spaces like real arteries," he says.

"Future research will focus on enhancing the autonomy level of the microrobot swarms, such as real-time feedback control of their motions and trajectories."

More information: Magnetic Swarm Intelligence of Mass-Produced Programmable Microrobot Assemblies for Versatile Task Execution, *Device* (2024). DOI: 10.1016/j.device.2024.100626. www.cell.com/device/fulltext/S2666-9986(24)00583-0
Journal information: Device

DNA origami builds nano-dinosaur, dancing robot 1000x thinner than human hair

Marking a significant advancement in molecular robotics, researchers have created custom-designed and programmable nanostructures using DNA origami.

The University of Sydney Nano Institute team employs "DNA origami," a technique harnessing DNA's natural folding abilities, the building blocks of life, to craft innovative biological structures.

As a proof of concept, the researchers created over 50 nanoscale objects, including a "nano-dinosaur," a "dancing robot," and a 150-nanometre-wide mini-Australia—about 1,000 times thinner than a human hair.

"This innovative approach has potential across a range of applications, from targeted drug delivery systems to responsive materials and energy-efficient optical signal processing," said the team, in a statement.

Programmable nano voxels

In the new study, researchers developed modular DNA origami voxels capable of forming intricate three-dimensional nanostructures.

Voxels have a wider range of applications since they extend into the third dimension, in contrast to pixels, which are just two-dimensional. Because of their great degree of customization, these programmable nanostructures enable the quick prototyping of a wide range of designs appropriate for numerous cutting-edge applications.

The team claims that the novel method is essential for developing nanoscale robotic systems for materials research, synthetic biology, and nanomedicine. By utilizing DNA's inherent folding characteristics, these structures can be customized for applications such as responsive material development, targeted medication delivery, or nanoscale precision manufacturing.

The technology's versatility enables applications such as adaptive materials that alter optical properties based on environmental changes and autonomous nanorobots capable of targeting and neutralizing cancer cells.

Drawing inspiration from construction methods like Meccano or string-based cat cradles, this technique replaces traditional materials with nanoscale biological components, unlocking new possibilities. DNA as a building material not only provides structural flexibility but also ensures compatibility with biological systems, making it ideal for medical and environmental applications.

The team highlights that the advancement marks a significant step toward creating dynamic, multifunctional nanorobots and materials with transformative potential across multiple scientific and industrial domains.

Adaptive nanobots

To assemble the voxels, the researchers attach additional DNA strands to the exterior of the nanostructures. These strands serve as programmable binding sites, functioning like color-coded Velcro, where only matching strands—determined by complementary DNA sequences—can connect.

The method provides precise control over voxel interactions, enabling the formation of customizable and highly specific architectures.

This technology holds immense promise, particularly in creating nanoscale robotic systems capable of precise drug delivery. Designed with DNA origami, these nanobots can detect specific biological signals, ensuring drugs are released only at the intended location and time. This approach not only improves the precision of treatments, such as cancer therapies but also reduces potential side effects by minimizing exposure to non-targeted areas.

Beyond drug delivery, the innovation extends to developing advanced materials with adaptive properties. These materials can respond dynamically to environmental changes, such as varying loads, temperature shifts, or fluctuations in acidity.

According to researchers, this adaptability makes them suitable for a wide range of applications, from medical devices to smart components in computing and electronics. By tailoring these materials to react to external stimuli, researchers aim to revolutionize fields that require precision, responsiveness, and enhanced performance in challenging environments.

“This work enables us to imagine a world where nanobots can get to work on a huge range of tasks, from treating the human body to building futuristic electronic devices,” said Dr Shelley Wickham, the research team leader at the University of Sydney, in a statement.

The team is exploring energy-efficient optical signal processing using DNA origami. This could enhance speed and accuracy in medical diagnostics and security.

China Unveils Spherical Robot Cop with Advanced AI and Facial Recognition

China has revealed a spherical police robot designed to autonomously pursue and immobilize criminals by shooting nets and rolling at speeds of up to 35 km/h.

Why it matters: China's latest law enforcement innovation, a spherical robot dubbed RT-G, combines artificial intelligence with facial recognition technology to create an autonomous police unit capable of operating on land and water. As reported by Fox News, the development signals a significant shift toward automated law enforcement.

The Big Picture: Cybernews reports that it was developed by Hangzhou-based Logon Technology, and the RT-G offers unprecedented capabilities:

- Speeds up to 35 km/h
- Withstands impacts up to four tons
- Operates autonomously using AI
- Deploys non-lethal weapons
- Costs between $41,300-$55,000

Technical Innovation: The robot's spherical design enables unique advantages:

- Amphibious operation in water and on land
- Advanced facial recognition for criminal identification
- Environmental disturbance sensors
- Non-lethal equipment including net guns and tear gas
- Ability to survive significant falls

Market Impact: The RT-G has attracted international attention:

- Middle Eastern buyers express strong interest
- Production costs remain relatively accessible
- Potential applications beyond law enforcement
- Adaptable for firefighting and rescue operations

Looking Forward: While the RT-G represents a significant advancement in automated law enforcement, its deployment raises important questions about privacy, ethics, and the role of human judgment in policing.

430,000x faster than reality: New physics engine accelerates AI robot training

430,000x faster than reality: New physics engine accelerates AI robot training

AI robotics training has been increased tremendously with the help of a new tool. Called 'Genesis', the tool is a new open-source computer simulation system.

Unveiled by a large group of university and private industry researchers, the system reportedly lets robots practice tasks in simulated reality 430,000 times faster than in the real world.

According to researchers, an AI agent is also planned to generate 3D physics simulations from text prompts.

Powered by a universal physics engine

Genesis, which is powered by a universal physics engine re-designed and re-built from the ground up, integrates various physics solvers and their coupling into a unified framework. This core physics engine is further enhanced by a generative agent framework that operates at an upper level, aiming towards fully automated data generation for robotics and beyond. The generative framework aims to automate generating data and multiple modalities.

Designed for general purpose robotics, embodied AI, & physical AI applications, the system is a universal physics engine that's capable of simulating a wide range of materials and physical phenomena.

Speech audio, facial animation

The system, which is lightweight, ultra-fast, pythonic, and user-friendly robotics simulation platform, is a powerful and fast photo-realistic rendering tool.

Researchers have maintained that currently, they are open-sourcing the underlying physics engine and the simulation platform. Access to the generative framework will be rolled out gradually in the near future, according to the research team.

The framework is aimed at integrating physically-accurate & spatially consistent videos, camera motion & parameters, human and animal character motion, robotic manipulation & locomotion policy, fully interactive 3D scene, speech audio, facial animation & emotion.

System leverages GPU-accelerated parallel computation

The team claims that Genesis is a highly-optimized physics engine that leverages GPU-accelerated parallel computation, with features like optimized collision checking, auto-hibernation, contact island, etc.

In large-scale simulation, Genesis utilized auto-hibernation to speed up simulation of entities that are in converged and static states. (This feature is under testing and will be released in version 0.1.1). When simulating a manipulation scene (with a single plane and a Franka arm), Genesis runs at 43 million FPS, which is 430,000 times faster than in real time, according to a statement by researchers.

“If an AI can control 1,000 robots to perform 1 million skills in 1 billion different simulations, then it may just work in our real world, which is simply another point in the vast space of possible realities. This is the fundamental principle behind why simulation works so effectively for robotics,” said Nvidia researcher Jim Fan, who contributed “a small part” to the project.

Empowered by a VLM-based generated agent

The research team also maintained that Genesis’s physics engine is empowered by a VLM-based generated agent that uses the APIs provided by the simulation infrastructure as tools to create 4D dynamic worlds, which can then be used as a foundational data source for extracting various modalities of data.

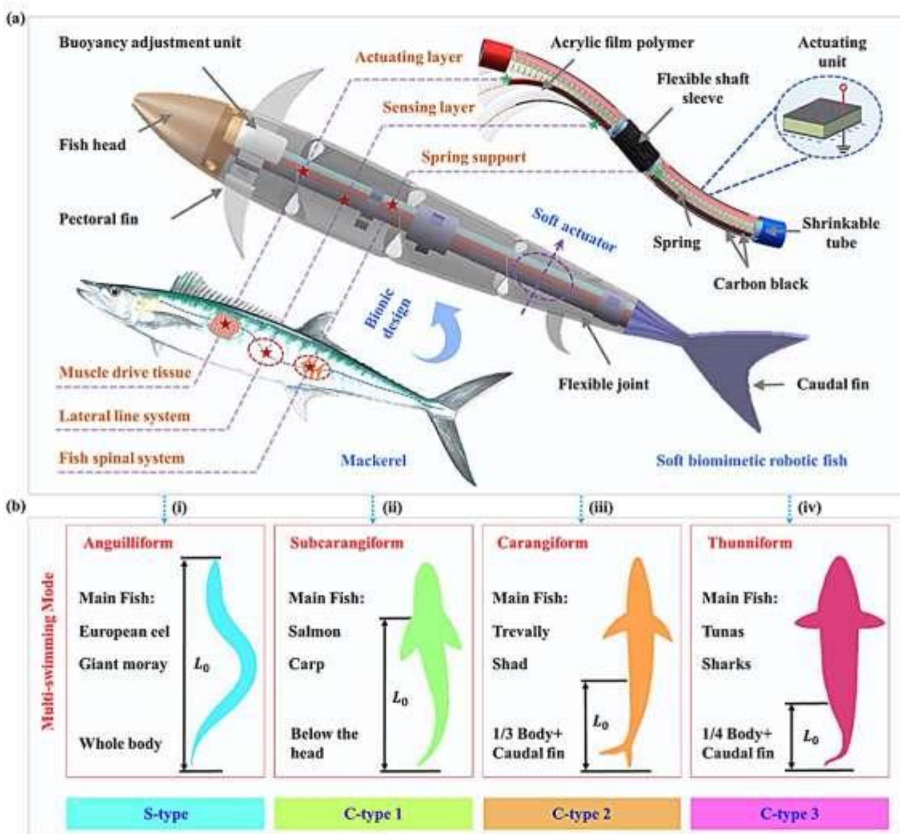
“Together with modules for generating camera and object motion, we are able to generate physically-accurate and view-consistent videos and other modalities of data,” said researchers.

"Genesis's physics engine is developed in pure Python, while being 10-80x faster than existing GPU-accelerated stacks like Isaac Gym and MJX. It delivers a simulation speed ~430,000 faster than in real-time, and takes only 26 seconds to train a robotic locomotion policy transferrable to the real world on a single RTX4090," said Zhou Xian, who has been part of the project is currently doing a PhD in robotics & AI from CMU Robotics Institute.

FEBRUARY 24, 2025

Soft robotic fish demonstrates advanced multi-mode swimming capabilities

by Zhang Nannan, Chinese Academy of Sciences



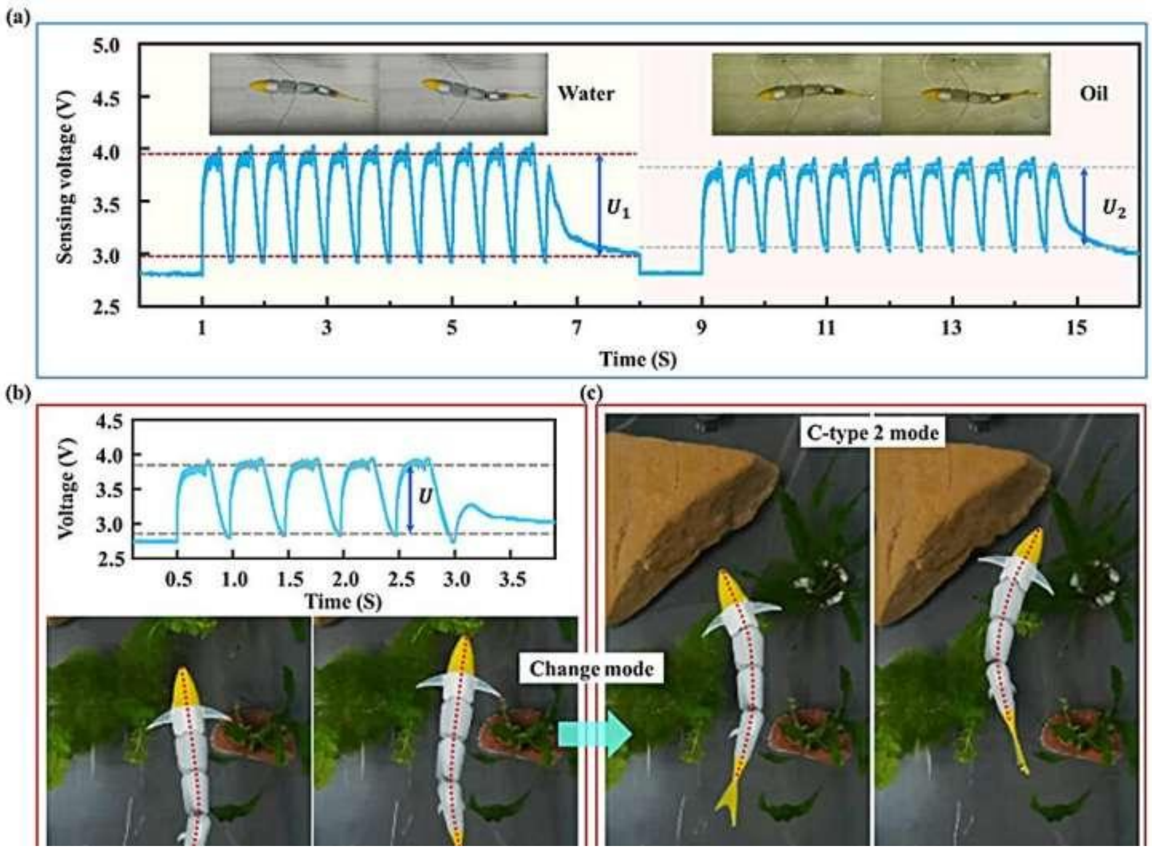
Bionic mechanisms of the soft robotic fish. Credit: Ruiqian Wang et al

Researchers from the Shenyang Institute of Automation of the Chinese Academy of Sciences have developed a multi-mode swimming soft robotic fish. Drawing inspiration from the highly sensitive lateral line sensing system and advanced muscle actuation mechanisms of natural fish, the new design integrates actuation, perception, and control capabilities, offering significant advancements in underwater robotics.

The study, published on January 21 in *IEEE Transactions on Robotics*, presents a soft robotic fish that can perform four distinct swimming modes, surpassing similar systems in both versatility and sensing capabilities.

The research marks significant progress in three critical areas: cooperative control strategies for multi-actuation units, the implementation of flexible embedded sensing systems, and intelligent environment-adaptive mode switching.

By mimicking the mackerel's biological structure, the researchers utilized 3D printing technology to design a flexible bionic structure paired with a soft actuator. The actuator integrates three specialized components arranged in functional layers: compression springs, dielectric elastomer membranes, and flexible electrodes.



Swimming characteristics of the robotic fish in different environments. Credit: Ruiqian Wang et al

To replicate the fish's lateral line system, which detects movement and environmental changes, the researchers developed high-precision flexible strain transducers. These sensors enable the robotic fish to sense its swimming state and changes in the surrounding fluid environment, allowing it to adaptively switch to the optimal swimming modes.

Furthermore, by synergistically controlling the excitation amplitude and sequence of multiple bionic muscle units, the robotic fish successfully reproduces the various swimming modes seen in natural fish and adapts to different swimming environments.

More information: Ruiqian Wang et al, Soft Robotic Fish Actuated by Bionic Muscle With Embedded Sensing for Self-Adaptive Multiple Modes Swimming, *IEEE Transactions on Robotics* (2025). DOI: 10.1109/TRO.2025.3532520
Journal information: IEEE Transactions on Robotics
Provided by Chinese Academy of Sciences