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Humanoid robotics in material and chemistry experiments

Yao Xu, Wentao Yang, Wenguang Tu and Xi Zhu*

The integration of humanoid robotics into materials science and chemistry represents a transformative evolution in experimental research, addressing persistent challenges such as reproducibility, scalability, and adaptability in increasingly complex workflows. Over the past decades, laboratory automation has transitioned from early mechanized systems [1–4] designed for repetitive tasks to highly specialized platforms integrating artificial intelligence (AI) [5–7] for experimental optimization. Despite these advancements, current technologies often fall short in cognitive and physical versatility, limiting their ability to manage dynamic, multidisciplinary experimental conditions. This limitation is further underscored by the significant budget cuts and closures of chemistry departments in the United Kingdom and the United States, a trend that reduces traditional research capacities while simultaneously increasing reliance on automation to sustain innovation [3,8].

Against this backdrop, humanoid robots emerge as a unique solution, combining the precision of traditional automation with human-like adaptability and decision-making capabilities. Unlike conventional robotic systems limited to repetitive tasks, humanoid robots are equipped with dynamic perception, real-time reasoning, and dexterous physical manipulation, allowing them to function effectively in complex experimental environments. As illustrated in Fig. 1, they bridge the gap between human researchers and rigid automation by integrating vision, gas sensing, cognitive AI, and adaptive motion control, enabling seamless interaction with diverse instruments and protocols in materials and chemistry laboratories. In Shanghai, specialized training grounds for humanoid robots are established [9], focusing on physical actions and integrating visual and gaseous sensing, making the city a hub for developing robots tailored for chemical and chemical engineering applications. The chemical laboratory itself is a critical application scenario for humanoid robots, providing an ideal environment for training and perfecting their functionalities. In recent years, the Chinese government has placed high emphasis on the development of humanoid robotics, enacting several policies. These policies have significantly propelled the industry forward while attracting many enterprises to invest in this sector. The Ministry of Industry and Information Technology's [10] stipulates that by 2025, an initial innovation system for humanoid robots will be established, with breakthroughs in key technologies such as the "brain, cerebellum, and limbs", and the whole machine products will reach an advanced international level and achieve mass production. By 2027, the technical innovation capacity of humanoid robots will be significantly enhanced, constructing an internationally competitive industrial ecosystem with comprehensive strengths reaching the world's advanced level. Therefore, it is projected that China will prioritize "industry first, consumption later" in achieving comprehensive mass production and commercialization of humanoid robots by 2025, focusing on advancing in more specialized technological segments.

Fig. 2 illustrates the evolution of laboratory automation over recent decades, emphasizing the rapid growth of automation-related publications alongside key technological advancements. Early automation tools focused primarily on improving reproducibility and precision for repetitive tasks. As AI-driven platforms emerged, they enabled high-throughput experimentation and expanded scalability. Today, humanoid robotics represents the next frontier, integrating advanced sensing, motion control, and artificial intelligence systems. This leap in adaptability and efficiency allows robots to support more dynamic, multidisciplinary workflows, overcoming longstanding challenges related to resource efficiency and experimental reproducibility [9,11,12]. The period from 2016 to 2025 marks an explosive rise in publications across biology, energy, and material sciences. Biology saw a dramatic increase, with the number of papers soaring from 431 in 2016–2020 to over 2300 in 2021–2025. Energy research also experienced notable growth, climbing from 69 papers to 506, while material science grew from 408 papers to 1477. All the relevant paper information is in the Supplementary Information. This surge reflects the transformative impact of advancements in AI, automation, and robotics, as these technologies continue to accelerate progress across multiple research fields, driving efficiency and innovation in complex, evolving laboratory environments.

Humanoid robotics demonstrates transformative potential across scientific disciplines by automating complex experimental workflows. In materials science, these systems optimize lithium-ion battery components through autonomous combinatorial synthesis and machine learning-driven parameter optimization, accelerating development cycles while reducing labor-intensive iterations [13]. Biomedical applications leverage robotic platforms for adaptive high-throughput drug screening, dynamically adjusting reaction parameters to enhance efficiency and reduce resource consumption. Extreme materials testing benefits from robotic capabilities to conduct experiments under harsh environmental conditions (extreme temperatures/pressures/corrosion), enabling critical advancements in aerospace and defense technologies [14,15]. Food safety implementations integrate AI-enhanced sensing for real-time contaminant detection and automated quality control, achieving unprecedented throughput in safety compliance. The integration of digital twin technology with artificial general intelligence (AGI) forms the technological

School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen, Shenzhen 518172, China
* Corresponding author (email: zhuxi@cuhk.edu.cn)

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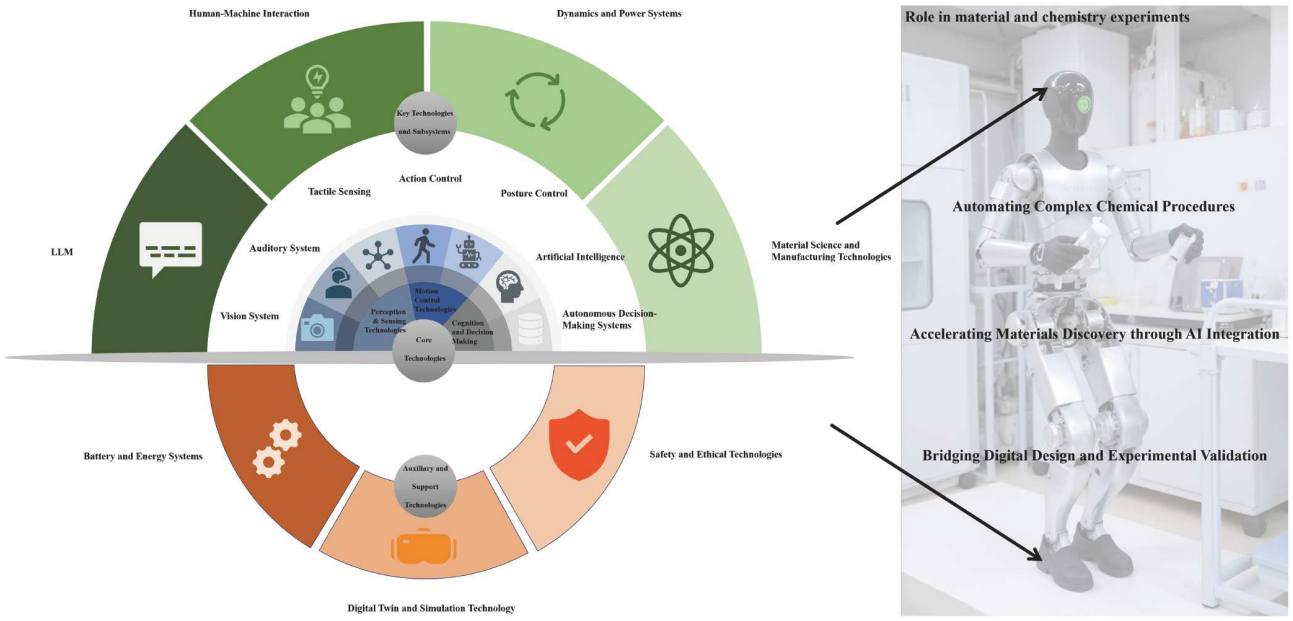


Figure 1 Conceptual illustration of humanoid robotics in material and chemistry experiments. The diagram outlines both the core technological components that define humanoid robots, such as perception, motion control, and AI cognition, and their key roles in laboratory settings, including automating complex chemical procedures, accelerating materials discovery, and bridging virtual design with experimental execution.

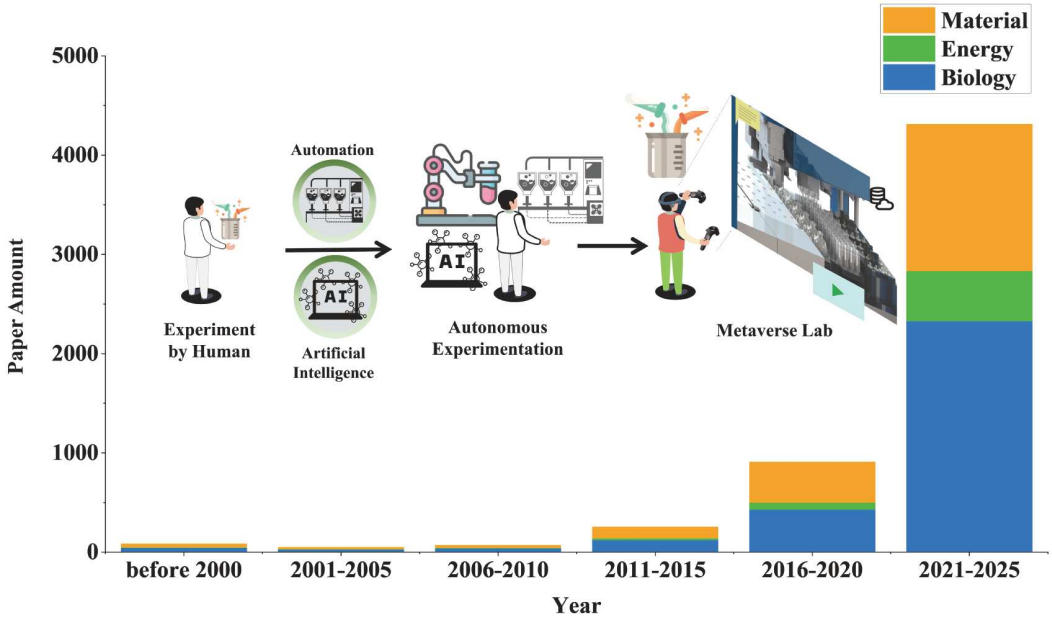


Figure 2 Historical progression of research publications in laboratory automation and robotics, highlighting key milestones and developments from early mechanized systems to autonomous research.

foundation for these advancements. Digital twins enable virtual simulation and optimization of experimental protocols prior to physical implementation, significantly reducing material waste while improving reproducibility through iterative feedback mechanisms [7,16]. AGI-equipped systems autonomously interpret complex datasets and adapt experimental protocols in real time, establishing new paradigms for sustainable laboratory research. This synergistic combination positions humanoid robotics as an emerging cornerstone of modern scientific investigation, particularly in materials science and chemistry, by creating collaborative frameworks that overcome traditional experimental limitations.

THE EVOLUTION OF LABORATORY AUTOMATION: BRIDGING DISCRETE AUTONOMOUS SYSTEMS WITH HUMANOID ROBOTICS

The development of humanoid robotics in laboratory automation is not merely an innovation but an inevitable outcome of decades-long progress aimed at addressing critical limitations in

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reproducibility, scalability, and adaptability. Traditional automation technologies—exemplified by solutions from Bruker, Siemens, and Opentrons—have been instrumental in advancing experimental workflows by excelling in precision and efficiency for well-defined, repetitive tasks. However, as research demands shift toward dynamic, multidisciplinary environments, the rigidity of such systems has become a bottleneck. Humanoid robots, with their ability to emulate human dexterity and cognitive capabilities, emerge as a natural progression: they bridge the gap between machine-like throughput and human adaptability, notably accelerating tasks like picking up and transferring a beaker with greater speed and success rates than many legacy systems. This integration signifies a new paradigm of smarter, more autonomous experimental workflows designed to accommodate the ever-increasing complexity of modern scientific discovery [17].

Fig. 3a centers on two essential dimensions of modern laboratory innovation. The first covers hardware platforms, from conventional machines and robotic arms to more advanced humanoid robots offered by various industry players. Machines and robotic systems typically excel at routine tasks, such as liquid handling or sample preparation, but often require extensive programming for novel workflows. Humanoid robots, by contrast, emulate human-like dexterity and can seamlessly adapt to changing experimental conditions. The second dimension addresses AI categories, namely Dry AI and Wet AI. Dry AI includes computational and predictive tools such as BERT or GPT-4, aiding in data processing and experimental design; Wet AI focuses on in-lab optimization, incorporating real-time feedback loops and closed-loop control to refine processes on the fly. Together, these technological pillars form the bedrock of contemporary automation, allowing for expanded capabilities that mitigate the traditional limits of precision robotics. In earlier generations, hardware-centric solutions were constrained by vendor-specific protocols and rigid workflows, while purely computational AI lacked the physical adaptability to manage diverse lab setups. By melding both hardware and AI in flexible frameworks, researchers can achieve improved accu-

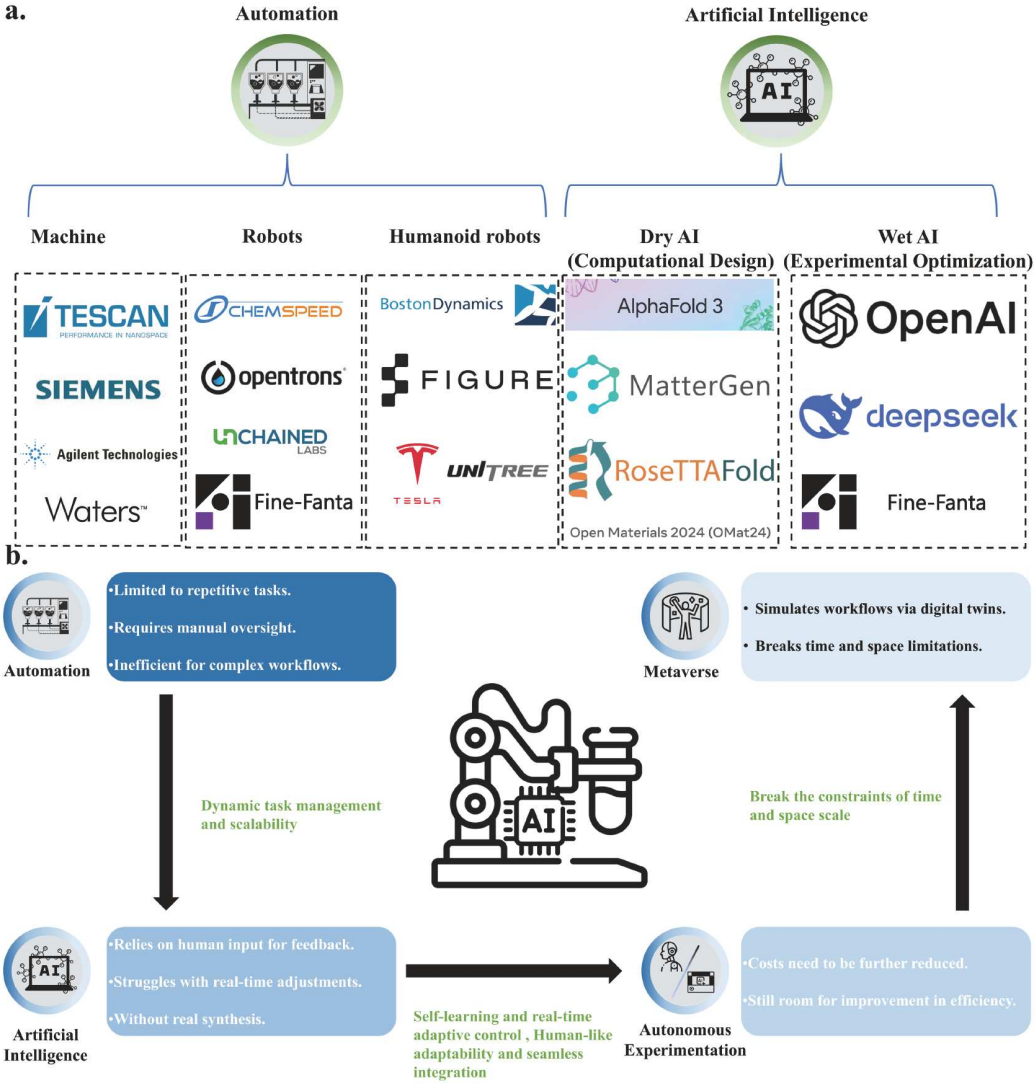


Figure 3 (a) Laboratory automation technologies spanning machines, robots, and humanoid robots, along with AI subdivided into "Dry AI" (computational/predictive) and "Wet AI" (laboratory optimization). (b) The broader evolution from basic automation to AI-driven research, autonomous experimentation, and Metaverse-centric laboratories.

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racy, reproducibility, and throughput. Yet, as laboratories tackle increasingly complex tasks—spanning multiple disciplines and requiring mid-experiment reconfigurations—the need for synergistic systems capable of real-time decision-making has become more urgent.

Fig. 3b provides a chronological map of how laboratory technology has evolved, moving through four major stages.

Basic automation: Traditional robotic systems handled repetitive tasks (e.g., liquid transfers, data logging), greatly enhancing speed and precision but remaining incapable of more dynamic or bespoke operations.

AI-driven platforms: Advanced computational tools offered real-time parameter optimization and data-driven insights, dramatically shortening experimental cycles and reducing trial-and-error. However, these platforms often could not physically interact with instruments or adapt to unexpected conditions.

Autonomous experimentation: Exemplified by Chemspeed and similar setups, self-learning mechanisms, and closed-loop experimentation minimized human oversight while refining multiple experiment iterations. Despite these gains, integration across heterogeneous lab systems was limited, constraining full-scale deployment in highly interdisciplinary settings.

Metaverse-centric laboratories: The latest paradigm integrates humanoid robots with digital twin technologies and immersive virtual environments. By leveraging advanced reinforcement learning and human-like dexterity, these systems unify diverse workflows into a seamless continuum, facilitating global collaboration beyond physical boundaries [18,19]. This approach not only expands scalability but also fosters standardized practices among distributed teams, propelling scientific discovery toward unprecedented levels of connectivity and efficiency.

Such transformations underscore the need for humanoid robotics, whose adaptive dexterity and cognitive capacity fulfill the requirement for more holistic automation. From simple mechanical tasks to high-level operational decisions, humanoid robots can orchestrate complex sequences with minimal manual intervention. Meanwhile, AI-driven solutions offer data-focused insights, optimizing everything from reagent selection to reaction conditions in real time. The result is a research environment where repetitive tasks are automated, complex protocols are managed dynamically, and cross-institutional teams collaborate via virtual platforms. In essence, this sweeping transition from basic automation to advanced humanoid robotics, further enriched by Metaverse technologies, represents a transformative shift in both materials science and chemical research. While earlier solutions highlighted either mechanical precision or computational optimization, the fusion of machine-like throughput, AI-driven intelligence, and near-human adaptability heralds a future where laboratories operate with unparalleled speed, flexibility, and connectivity. Consequently, scientific discovery accelerates, transcending traditional barriers of location or equipment constraints, and reshaping the landscape of research for generations to come.

BRIDGING THE GAP: HUMANOID ROBOTICS ENABLING SEAMLESS INTEGRATION OF AI AND EXPERIMENTATION

In contemporary scientific research, the transition from theoretical concepts to real-world experimentation still relies heavily on human involvement. Although AI-driven platforms have demonstrated significant potential in generating hypotheses and designing novel molecular structures, researchers remain the primary "bridge" among disparate instruments when putting these insights into practice. Traditional automation systems, though efficient in handling repetitive tasks, struggle with complex and dynamic workflows; they excel at high-throughput, standardized operations yet lack the flexibility and adaptability needed for diverse protocols and equipment. Consequently, a pronounced gap persists between "autonomous experimentation" and "seamlessly integrated experimental workflows".

Fig. 4 illustrates three key stages in advancing from innovation to new materials: manual experimentation, half-automated experimentation with humans, and the combined approach of humanoid robots plus autonomous platforms. Even with conventional automation, significant human effort is needed to adapt to unforeseen conditions, integrate data from multiple sources, and fine-tune operations in real time. In contrast, humanoid robots offer near-human dexterity and can seamlessly interface with various lab instruments, adjusting procedures on the fly based on AI-generated feedback. By leveraging digital

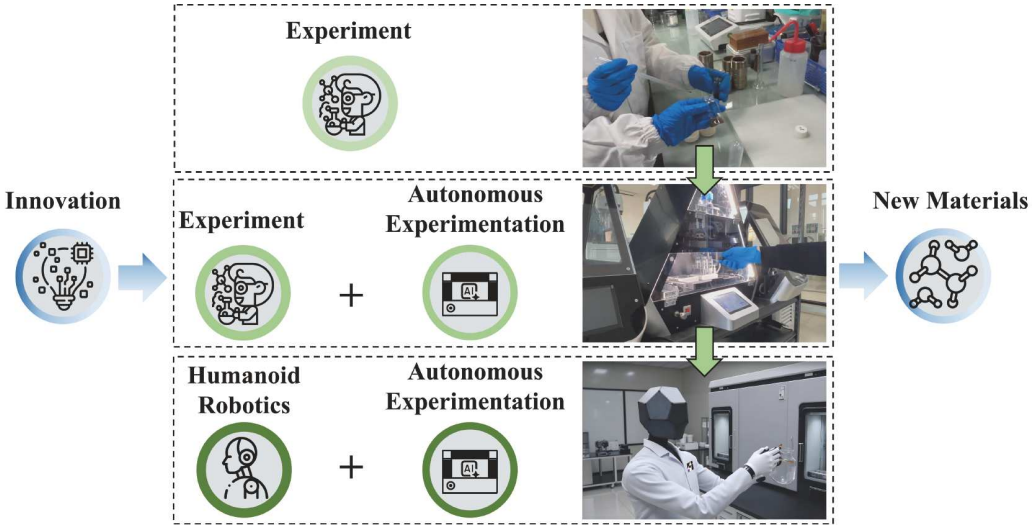


Figure 4 Transition from manual to humanoid robotics involved experimentation (All examples are from Hangzhou Fine-Fanta Technology Co., Ltd.).

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twin technology, they can also simulate experiments virtually before performing them physically, thereby reducing both resource consumption and error rates. However, deploying humanoid robots from controlled laboratory settings to full-scale industrial production lines presents cost and complexity challenges that are not always straightforward to quantify. Thorough training and validation in the lab, covering safety protocols, response to unexpected scenarios, and operational best practices, are essential prerequisites for meeting the stricter requirements of factory environments. Only after this rigorous phase can humanoid robots truly realize their potential to surpass traditional automation systems in terms of adaptability and throughput. From a cost perspective, a single humanoid robot might demand an initial investment for hardware and integration. Yet this can be offset over time if the robot replaces multiple human operators in wages and benefits. Beyond such financial considerations, the capacity for round-the-clock operation and rapid reconfiguration underscores the unique advantages of humanoid robotics. Ultimately, by bridging the gap between AI-driven design and hands-on experimentation, these systems pave the way for faster, more reliable material discovery and set the stage for transformative industrial applications.

The emergence of humanoid robotics-driven experimentation systems heralds a transformative leap in scientific automation, fundamentally addressing three persistent dilemmas in modern materials chemistry research: the gap between theory and experiment, the rigidity of multidisciplinary workflows, and the geographical constraints on innovation scalability. Supported by Chinese policies, especially in cities such as Shanghai, where dedicated training grounds have been established, these systems integrate multimodal AI cognition, adaptive mechatronic control, and digital twins fused with the metaverse, enabling seamless transitions between computational design and physical validation. Their anthropomorphic form ensures compatibility with conventional laboratory setups while introducing human-like flexibility for non-standard scenarios. Currently, humanoid robots are gaining traction as experimental agents, but their importance will grow as research becomes increasingly automated, complex, and decentralized. Development trends point toward tighter integration with AI frameworks such as federated learning and reinforcement learning, improving collaborative knowledge acquisition across cloud laboratories. In the future, humanoid robotics is expected to move beyond lab-based applications toward scalable deployment in chemical production, materials development, and smart manufacturing. As these platforms evolve, they will help reshape scientific discovery, from hypothesis-driven experimentation to real-time, AI-guided knowledge generation, establishing a new foundation for materials and chemistry research.

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1 Canty RB, Abolhasani M. Reproducibility in automated chemistry laboratories using computer science abstractions. Nat Synth, 2024, 3: 1327–1339
2 Abolhasani M, Kumacheva E. The rise of self-driving labs in chemical and materials sciences. Nat Synth, 2023, 2: 483–492
3 Tilley L, Woodburn M, Vincent S, *et al.* Systematic design of a natural sciences collections digitisation dashboard. RIO, 2024, 10: e118244
4 Angelopoulos A, Cahoon JF, Alterovitz R. Transforming science labs into automated factories of discovery. Sci Robot, 2024, 9: eadm6991
5 Wallach I, Bernard D, Nguyen K, *et al.* AI is a viable alternative to high throughput screening: a 318-target study. Sci Rep, 2024, 14: 7526
6 Liu C, Zhang H. Data processing for high-throughput mass spectrometry in drug discovery. Expert Opin Drug Discov, 2024, 19: 815–825
7 Weidlich R, Albrecht T, Derr P, *et al.* Designing a process-oriented digital twin for industrial testing laboratories. IEEE Trans Eng Manage, 2024, 71: 15174–15187
8 Fan J, Zheng P, Lee CKM. A vision-based human digital twin modeling approach for adaptive human-robot collaboration. J Manufacturing Sci Eng, 2023, 145: 121002
9 Tong Y, Liu H, Zhang Z. Advancements in humanoid robots: a comprehensive review and future prospects. IEEE CAA J Autom Sin, 2024, 11: 301–328
10 Xu C, Wang Y, Mo Y, *et al.* Humanoid robot technology and industry development. Strategic Study CAE, 2025, 27: 150–167
11 Qu W, Li J, Zhang R, *et al.* Adaptive planning of human–robot collaborative disassembly for end-of-life lithium-ion batteries based on digital twin. J Intell Manuf, 2024, 35: 2021–2043
12 Ismail MN, Abbas HH, Mejbel BG, *et al.* Complex dynamics at the intersection of computer algorithms and robotic function. In: 2024 36th Conference of Open Innovations Association (FRUCT), Lappeenranta: IEEE, 2024. 527–537
13 Passalacqua M, Pellerin R, Yahia E, *et al.* Practice with less AI makes perfect: partially automated AI during training leads to better worker motivation, engagement, and skill acquisition. Int J Hum–Comput Interaction, 2025, 41: 2268–2288
14 Yuan G, Lv F, Shi J, *et al.* Integrated optimisation of human-robot collaborative disassembly planning and adaptive evaluation driven by a digital twin. Int J Production Res, 2024, 35: 2021–2043
15 Huang J, Liu H, Junginger S, *et al.* Mobile robots in automated laboratory workflows. SLAS Tech, 2025, 30: 100240
16 Rihm SD, Tan YR, Ang W, *et al.* The digital lab facility manager: automating operations of research laboratories through "The World Avatar". Nexus, 2024, 1: 100031
17 Sanders LM, Scott RT, Yang JH, *et al.* Biological research and self-driving labs in deep space supported by artificial intelligence. Nat Mach Intell, 2023, 5: 208–219
18 Wang H, Fu T, Du Y, *et al.* Scientific discovery in the age of artificial intelligence. Nature, 2023, 620: 47–60
19 Rihm SD, Bai J, Kondinski A, *et al.* Transforming research laboratories with connected digital twins. Nexus, 2024, 1: 100004

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Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Supplementary materials are available in the online version of the paper.



Yao Xu obtained his BC degree from Hunan University in 2018. He completed his PhD degree in 2023 at the Chinese University of Hong Kong, Shenzhen, focusing on integrating large language models (LLMs) with autonomous materials discovery systems. His pioneering research bridges artificial intelligence and reticular chemistry, developing novel frameworks that accelerate the innovation cycle from material design to industrial application.

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Xi Zhu obtained his BC degree in the Special Class for the Gifted Young and Hefei National Laboratory for Physical Science at the Microscale, University of Science and Technology of China, in 2006, and PhD degree from Nanyang Technological University, Singapore, in 2011. His research focuses on the AI application in materials science and new energy engineering. He leads the development of intelligent robotics, promoting the new advances of materials science in the AI era.

材料化学实验中的人形机器人

徐曜, 杨文涛, 涂文广, 朱熹*

摘要 将人形机器人技术引入材料科学与化学领域，标志着实验研究迈入了革命性新时代，有效解决了复杂实验流程中长期存在的可重复性、可扩展性和适应性难题. 过去数十年间, 实验室自动化已从仅能执行重复性任务的早期机械化系统，逐步发展到借助人工智能进行实验优化的高度专业化平台. 然而, 现有方案往往缺乏在动态、多学科实验中所需的认知与物理多功能性. 在此背景下, 人形机器人提供了极具吸引力的替代选择，兼具传统自动化的高精度与人类决策的灵活适应能力. 不过, 要将人形机器人从实验室推广到实际工厂生产线上, 还需面对成本投入难以量化的挑战: 只有先在实验室里对其进行充分的训练和验证, 完善操作规范与安全策略, 并积累应对各类突发状况的实操经验, 才能为化工环境所要求的更高灵活度和通用性奠定基础, 从而充分发挥人形机器人在材料化学实验中难以企及的独特优势.

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