Current Researches and Future Development Trend of Intelligent Robot: A Review

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Current Researches and Future Development Trend of Intelligent Robot: A Review

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Abstract: With the advancing of industrialization and the advent of the information age, intelligent robots play an increasingly important role in intelligent manufacturing, intelligent transportation system, Internet of things, medical health and intelligent services. Based on working experiences and reviews on intelligent robot studies both in China and abroad, the authors summarized researches on key and leading technologies related to human-robot collaboration, driverless technology, emotion recognition, brain-computer interface, bionic software robot and cloud platform, big data network, etc. The development trend of intelligent robot was discussed, and reflections on and suggestions to intelligent robot development in China were proposed. The review is not only meant to overview leading technologies of intelligent robot all over the world, but also provide related theories, methods and technical guidance to the technological and industrial development of intelligent robot in China.

Keywords: Intelligent robot, human-robot collaboration, driverless technology, emotion recognition, brain-computer interface, big data network.

1 Introduction

1.1 Introduction and classification of intelligent robots

Year 2015 witnessed the birth of intelligent robot[1]. With the emergence of artificial intelligence era, robotics technology, information technology, communication technology and artificial intelligence are further integrated. Robot is welcoming a new age of intelligence after a long time evolvement at electrical age and digital age. The whole process is reflected on three aspects: Firstly, traditional industrial technologies like controller, servo motor and reducer have changed into artificial intelligence technologies like computer vision, natural language processing and deep learning; Secondly, robots have integrated into human society more deeply, attracting attentions from both industrial users and commercial, family and individual users; Thirdly, the once mutual independent human-robot relationships are replaced by a tie of collaboration and interaction.

International standardization organization (ISO) defines robot as an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks. A robot includes the control system and interface of the control system[2]. Intelligent robot is a machinery system that has comprehensive improvements in perception, decision-making and performance compared with traditional robot, and can simulate human behaviors, emotions and thinking. With a smart "brain", they can follow human commands, and accomplish tasks according to preset programs, learning and improving their behaviors while interacting with human beings. Such highly intelligent robots are widely applied to different fields, which arouse people′s infinite interests and massive imaginations. Robots provide samples to evaluate artificial intelligence technology. On one hand, they can be used to comprehensively investigate technologies in different artificial intelligence fields and to figure out their mutual relationships. On the other hand, they can release people from dangerous, harmful, repeated and heavy-loaded works, as well as those carried out in the sky or deep sea, or demanding high precision that far beyond the competence of human beings. In no doubt, the role of intelligent robots in social life and production will be more important than ever.

From the perspective of the application environment, intelligent robots can be divided into industrial robots, service robots and specialized robots[3].

Industrial robot is the robot with multi-joint manipulators or multi-degree of freedom for industrial field. It is a self-controlled and self-powered machinery device that can move automatically and finish various tasks. After re-

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ceiving human commands, industrial robot will plan motion path and then start operating according to the preset programs, including welding, coating, assembling, collecting, placing (e.g., packaging and stacking) and making product detection and test. Based on the basic mathematical model conducted at the XYZ rectangular coordinate system, the serial multi-axis manipulator, one kind of industrial robot, each of whose joints stands as one single working unit and is driven by servo motor or stepping motor, can follow the controllable trajectory to reach any point in the coordinate system. SCARA robot, a cylindrical robot used in industrial production, can work for plane positioning and vertical assembling. Parallel multi-degree-of-freedom manipulator, which behaves robustly to dynamic error, frees from accumulative error and can reach high precision, has compact structure, high rigidity and large carrying capacity. Automated guided vehicle (AGV), equipped with automatic guidance devices such as electromagnetic or optical sensors, can move along the prescribed path with safety insurance, and can finish various transfer tasks.

According to the definition of International Federation of Robotics (IFR), service robot is a "robot that performs useful tasks for humans or equipment excluding industrial automation applications"[4]. For example, the domestic servant robots, such as intelligent sweeping robots and window cleaning robots, can work as human assistants to do housework. They can also provide navigation services, automatically making path planning and avoiding obstacles. Other kinds of service robots, like family socialization robots, companion robots, mobile assistant robots and pet exercising robots, are able to interact with people, as well as completing delivering missions, caring for elderly and children, reminding events and patrolling houses. Similarly, the education and entertainment robots construct open learning platforms for consumers, and help developers to make deep studies based on the feedback data. Besides, some robots, namely emotional communication robot, children education robot, intelligent robot learning platform, personal UAV, personal mobility robot, humanoid robot and robotic pet, are supported by interactive voice technology which allow communication and emotional interaction with humans. The commercial service robots, including reception robot, shopping guide robot, cooking robot, office robot, security robot, can customize personalized services according to application scenarios, and complete tasks such as advertising, providing consultation and guidance, assisting office work, making security patrol, etc.

Specialized robots are robots that apply to special environments. They can assist in completing tasks in dangerous and harsh environment or tasks requiring high precision. For example, the medical robots provide advanced solutions to surgical treatment and rehabilitation, which is significant for reducing the difficulty of surgery and treatment, and shortening the recovery time, such robots include master-slave surgical robot, orthopedics robot, capsule endoscopy robot, rehabilitation robot, intelligent prostheses, aged service robot and nursing robot. The military robots, including reconnaissance robots, battlefield robots, minesweeper robots and military UAVs, have a long history and have already been put into the battlefield, which make contributions to material transportation, search and exploration, anti-terrorist rescue and military attack. The anti-terrorist and rescue robots consist of EOD robots, fire-fighting robots, life detection and rescue robots, etc. Concerning with the exploration cause, space robots, underwater robots, and pipeline robots have presented impressive performance. In addition, there are some robots for scientific researches and cutting-edge applications, including nanorobot, bionic robots, swarm robots, etc.

1.2 Intelligent robot development plans of countries in the world

Robotics technology is a complicated and advanced technology that involves multi-fields and multi-disciplines, including electro-mechanics, automation control, sensor technology, computer technology, new material, bionic technology and artificial intelligence. It is accepted as one of the high technologies that exerts great importance to future development of emerging industries. As an important technological platform, it not only provides key support for the development of advanced manufacturing, but also leads a way to high-quality life.

Intelligent robot industry sets a significant standard to evaluate the technological innovation and high-end manufacturing level of a country. Its development is attracting more and more attentions in the world. In order to seize development opportunities and gain competitive edges in high-tech fields represented by robot, major economic entities in the world have successively formulated national strategies on robot industry development, and realized a series of breakthroughs in robotics technologies. Some foreign countries studied robot early and now have relatively mature technologies. For instance, the United States, several European countries, Japan and South Korea have all made robot development strategies and plans according to their own productivity demands.

1.2.1 Robot development plan of America

America is the first country that develops and promotes application robots, keeping its leading role in intelligent robot technologies in the world. Recently, America has formulated and issued several strategies and plans related to robot development. In 2011, America launched the plan of *Advanced Manufacturing Partnership* (AMP) which declared clearly that revitalizing American manufacturing industry by industrial robot, developing a new generation of intelligent robot based on the advantage of information network technology, and investing 70 million US dollars for the research of next generation robots[5]. In the same year, Carnegie Mellon University launched the *National Robot Plan*, aiming to help "USA keep the leading role in the next generation of robot technology and applications"[6]. The *Robot Roadmap*: *From Internet to Robot* was published in 2013, which placed intelligent robot and the 20th century internet at the equal important position, and emphasized the importance of robotics technology in manufacturing and medical health. The latest version of *robot roadmap* was issued in 2016, which offered technical and policy guidance to applications of robots in unmanned driving, human-robot collaboration and nursing education[7]. In the same year, *National Robot Plan 2.0* was launched, which was devoted to creating ubiquitous collaborative robots to set a symbiotic relationship between robot and human[8].

1.2.2 Robot development plans of European Countries

In Europe, robotics technological innovation has been a key prior field in the European Union's *Digital Agenda*[9], *the 7th R&D Framework Plan*[10] and *2020 Project Horizon*[11]. UK launched the first official robot strategy *RAS 2020* and invested 257 million US dollars for development of *Robot and Automatic System* (RAS) in 2014, aiming to occupy the leading status in robot industry[12]. In 2013, the "*Industrial 4.0 Plan*" of Germany which intends to maintain its pioneering role in manufacturing industry also took intelligent robot and intelligent manufacturing technology as the starting point of its new industrial revolution[13]. In the same year, France issued the *French Robot Initiative* and planned to invest 129.6 million US dollars to robot industry, aiming to create favorable conditions for sustainable development of robot industry and realize the goal of "ranking top 5 in world robot field by 2020"[14]. In 2014, funded by the Commission of European Union and European Robot Association, EU started the EU Robot R&D Plan which became the largest non-government self-service robot innovation plan in the world. By 2.8 billion euros investment till 2020, the plan is expected to create 240 000 jobs, and gather the strengths of more than 200 companies and 12 000 R&D researchers to stimulate robots applications in manufacturing, agriculture, health care, transportation, safety and family[15].

1.2.3 Robot development plan of Japan

As the biggest robot power, Japan has attached great importance to the robot industry and formulated a long-term development strategy for robotics technology. Meanwhile, the Japanese government plans to fully tap the potentials of robot industry, taking it as an important pillar to support national economic growth. In June 2014, the *Japan Revitalization Strategy* was proposed with the intention to launch a new industrial revolution driven by robots. In September, a *Robot Reform Committee* was founded, in which several experts were invited to discuss technological progress related to robot reform, supervision reform and global standard of robot technology[16]. The development of industrial robot is listed among three key tasks in the new century. In 2015, *New Strategy on Robot* was issued, aiming to deeply integrate robot with computer technology, big data, network and artificial intelligence, thus positively creating a worldwide robot technological innovation highland in Japan, fostering a world-class robot application society, and leading the development of intelligent robot in the new era[17].

1.2.4 Robot development plan of the Republic of Korea

The Republic of Korea views intelligent robot as one of the ten industrial engines to facilitate national economic growth in the 21st century. *Promotion Laws on Intelligent Robot* was formulated in March 2008[18]. The *Basic Plan of Intelligent Robot* was released in April 2009. The government hopes to enhance competitiveness of domestic robot industry and gradually accomplish transformation from traditional manufacturing robot to intelligent service robot through a series of positive policies and efforts on technological research and development. In the same year, the *Service Robot Industrial Development Strategy* was born, hoping to rank top in the world robot industry. In 2012, the government launched the *Future Robot Strategy 2022* for the next 10 years, with a planned investment of 350 billion won to expand ten fold of the current robot industry that is worth about 2 trillion won to 25 trillion won by 2022. This strategy focuses on the development of rescue robot, medical robot, intelligent industrial robot and domestic use robot, aiming to develop robots as a pillar industry and finally embracing an all-robot era[19]. Based on this strategy, the Ministry of Knowledge Economy formulated the *Second Intelligent Robot Action Plan* (2014-2018) in 2013, which requested clearly to increase the national robot GDP to 20 trillion won and robot export volume to 7 billion US dollars, taking 20% of global market shares by 2018 and ranking top three in the world robot industry.

1.3 Significance and prospect of intelligent robots

President Jinping Xi always mentions that "robot is the 'pearl on the top of manufacturing crown' and its research and development, manufacturing and application are important symbols of one country's technological innovation and high-end manufacturing level"[20]. In the *Robot Industrial Development Plan* (2016-2020) co-issued by China's Ministry of Industry and Information Technology, State Development and Reform Commission and Ministry of Finance, the development and application of intelligent robot stands as a primary development task. It also sets goals of "achieving technological breakthroughs in new generation of robot, realizing innovative applications of intelligent robot, developing middle and high-end industrial robot and applying service robot to more field"[21].

Intelligent robotics technology requires integration of different disciplines. With the maturing development of big data, artificial intelligence and sensor technology, robot gradually transforms from traditional industrial robot to intelligent robot with abilities of perception, analysis, learning and decision-making. Intelligent robot can deal with abundant information and accomplish very complicated tasks. It will play an even more important role in future industry, agriculture, transportation, medical health, education, entertainment, aerospace and military.

With sharp growth of labor cost in China, the demographic dividend is diminishing gradually[22]. Since the production mode is becoming flexible, intelligent and refined, it is urgent to create a new manufacturing system on intelligent manufacturing. Future demands for more intelligent industrial robots will welcome a blowout growth[23]. On the other hand, China is stepping into an aging society. Accordingly, social service cost is increasing, resulting in sharp growth of demands for elderly caring and medical services[24]. Development and promotion of intelligent service robots will fill the gap caused by shortage of professional service workers and benefit people's daily life. In addition, national defense and military, unknown exploration and public security will require great investments for the development and application of intelligent robots which can help people to accomplish high-risk tasks in severe environment.

In summary, intelligent robot industry has great market potentials and will embrace promising development. Wide application of intelligent robots will free human labors significantly from complicated, repeated, basic and high-risk works. Intelligent robot not only creates great economic benefits for the society, but also effectively improves people's life standards. Strategically, it is very important to develop and promote intelligent robotics.

Under a time of "ubiquitous computing", people have entered into a new age of intelligent machine. In the next few years, artificial intelligence and robot will have far more profound impact on the world than reforms by personal computers and the Internet in the past 30 years. Now, it is the best time to develop intelligent robot vigorously. Robot development toward intelligence will become a starting point of the "*Third Industrial Revolution*" and an important economic growth drive, thus influencing the global manufacturing pattern. Owning the largest robot market in the world, China should keep alert to the world changes and make overall plan to integrate superior resources, seek breakthroughs in key technologies and occupy the highland of technology and market so as to overtake other countries in high-tech competitions. That is an opportunity, as well as a challenge for a country.

2 Status of intelligent robot

2.1 Industrial development status of intelligent robot

The recent years have witnessed the expanding and prosperity of global robot market, which brings progress and mature of robot technologies. A group of representative robot research institutes and famous enterprises emerge successively both in China and abroad. Research institutes include MIT Computer Science and Artificial Intelligence Laboratory, Stanford Artificial Intelligence Laboratory, the Robotics Institute of Carnegie Mellon University (CMU), Human-Computer Interaction Institute of Georgia Institute of Technology, Humanoid Robotics Institute of Waseda University, Intelligent Robot Laboratory of University of Tsukuba, German Aerospace Center (DLR) Robotics and Mechatronics Center, Shenyang Institute of Automation of Chinese Academy of Sciences, Robotics Institute of Shanghai Jiaotong University, Robotics Institute of Harbin Institute of Technology, Institute of Automation of Chinese Academy of Sciences, Robotics Institute of Beihang University, Intelligent Robot Institute of Beijing Institute of Technology, etc. These research units are pioneering teams of robot technologies in the world, which have made outstanding contributions to the research of intelligent robotics.

There are many famous robot companies around the world, such as ABB Company (Switzerland), KUKA Company (Germany), Yaskawa Electrics Company and FANUC Company (Japan), Northrop Grumman Company, iRobot Company and Intuitive Surgical Robot Company (USA), ABP Company (UK), Saab Seaeye Underwater Robot Company, Reis Robot Group (German), Pesco Company (Canada) and Aldebaran Company (France), and Chinese companies like Xinsong Robot Automatic Co., Ltd, Harbin Boshi Automatic Co., Ltd, Nanjing Estun Company, Anhui Effort Company, Guangzhou Numeral Control Robot Company, Dajiang Innovative Technology Company, Ninebot Robot Company, Foxconn Technology Group, Shenzhen Youbixuan Robot Company, Homelite Youlan Company, Pangolin Robots, Beijing Tianzhihang Robot Company and Beijing Bohuiweikang Company[23]. These enterprises have formed pillar industries in their own countries or local areas, and have made indelible contributions to the application and marketization of robot products.

Additionally, some powerful enterprises or research institutes will organize robot competitions to accumulate solutions to problems of specific industries or fields, famous ones include Amazon Item Pick Challenge Competition of Logistics Industry[25], Urban Challenge of Unmanned Driving[26], DARPA Robot Challenge[27], NASA Sample Return Robot Challenge[28], etc. These robot competitions have attracted wide attentions around the world. They not only promoted robot technologies effectively, but also provide good opportunities for exercise and big platforms for communications among robot development and application teams.

As the global robot market continuing expanding, industrial robot, specialized robot and service robot are applied to even wider fields, which enables the global robot industry to witness a new round of growth. According to Fig.1 which represents the global robot size in 2017, the whole value of global robot market is expected to reach 232 billion US dollars by 2017, and the average growth rate from 2012 to 2017 is nearly 17%. Industrial robot accounts for 14.7 billion US dollars, while service robot and specialized robot take up 2.9 billion US dollars and 5.6 billion US dollars, respectively[29]. In the following text, the industrial development of robot will be analyzed from the perspectives of industrial robot, service robot and specialized robot.

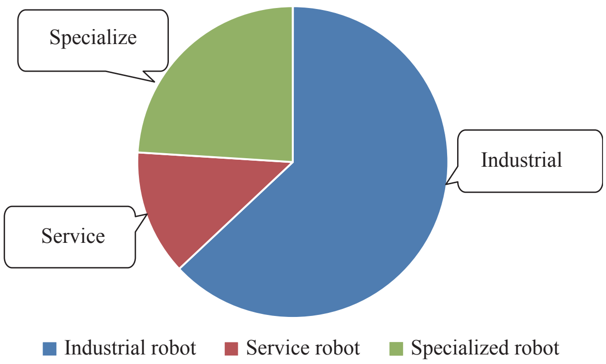


Fig. 1 Global robot market size in 2017[29]

2.1.1 Development status of industrial robot

In the area of industrial robots, the continuous demand of automation industry has brought a continuous growth in the sales of industrial robots[30]. The automobile industry is still the largest consumer, while electronic industry and metal mechanical industry are main driving forces of quantity growth of industrial robots. Fig.2 represents the global sales volume and growth rates of industrial robots from 2012 to 2020. From 2012 to 2016, the average annual growth of industrial robot sales volume was 15.2% (CAGR), which was increased by 80.8%. According to IFR statistics, the global sales volume of industrial robots exceeded 13.2 billion US dollars in 2016, which increased 14.2% than 2015.

Asia is the largest consumption market of industrial robot, with a sales volume up to 7.6 billion US dollars. Europe and America are the second largest consumption market, with sales volume reaching 2.64 billion US dollars and 1.79 billion US dollars respectively. Total sales volume in China, Korea, Japan, America and Germany takes up 3/4 of the global sum. The great demands of industrial automation in these countries activated the industrial robot market and brought a sharp growth in consumption of industrial robot in the world. Currently, the average consumption proportion of industrial robot in global manufacturing field was higher than 70 robots per 10 000 people.

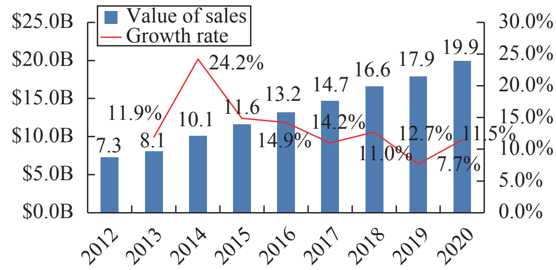


Fig. 2 Global sales volume and growth rates of industrial robots from 2012—2020[29]

China has been the biggest industrial application market in the world since 2013 and the demands for industrial robot increase continuously. China's domestic sales volume of industrial robot in 2016 was 31.3% which is higher than that in 2015. It is expected that China's sales volume of industrial robot in 2017 will exceed 110 000 for the first time and the market size will reach 4.22 billion US dollars.

2.1.2 Development status of service robot

For service robot, America ranks top in terms of studies on medical robot, logistics robot and military robot. Europe possesses advantages in medical robot and domestic use robot, while China achieves significant progresses in service robot in logistics, medical health and entertainment[31]. The service robot market develops quickly, which is stimulated by artificial intelligent technological development, continuous refining on application scenes and patterns for service robot, and continuous growth of diversified demands. As what is shown on Fig.3, the global service robot market is expected to reach 2.9 billion US dollars in 2017, and 6.9 billion US dollars in 2020. The average growth rate from 2016 to 2020 is 27.9%. Logistics systems, defense applications and field robots are still the top three of robot consumption. Logistics systems and medical fields are believed to be markets with the greatest development potentials. In 2017, the global market values of medical robots, domestic use robots and specialized robot will reach 1.62 billion US dollars, 0.78 billion US dollars and 0.5 billion US dollars respectively, among which medical robots take the largest share of 55.9%.

China's accelerating aging process boosts demands for medical and education services, which in return, brings China a great development space for service robot. In 2016, China's market value of service robot was 1.03 billion US dollars. It is expected to reach 1.32 billion US dollars by 2017, showing a year-on-year growth of 28%. It will be higher than 2.9 billion US dollars by 2020.

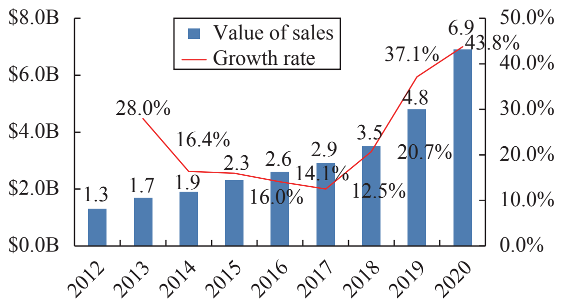


Fig. 3 Global sales volume and growth rate of service robot from 2012—2020[29]

2.1.3 Development status of specialized robot

With the continuous improvement of overall performance and emergence of new applications and markets, specialized robots in disaster rescue, bionic and human-carrying fields have attracted high attentions from countries around the world. As what is shown on Fig.4, the global market value of specialized robot will reach 5.6 billion US dollars in 2017. With an annual average growth rate of 12% from 2016—2020, the market value will reach 7.7 billion US dollars in 2020.

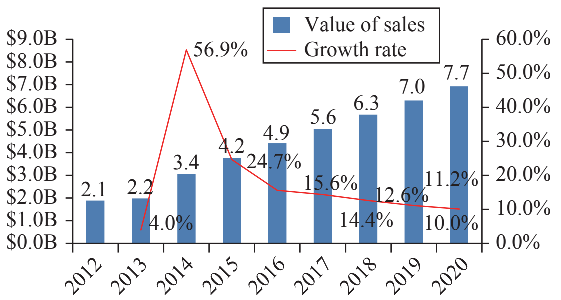


Fig. 4 Global sales volume and growth rate of specialized robot from 2012—2020[29]

China's demands for specialized robots increase continuously in order to respond to natural disasters and emergency incidents, including earthquakes, flood and fire disasters, and security threats. The market value of specialized robot in China was 0.63 billion US dollars in 2016, increasing by 16.7%, which is higher than the global growth rate. The market values of robots for military use, limit-environment work and emergency rescue are 480 million US dollars, 110 million US dollars and 40 million US dollars respectively, the growth rate of which used in limit environment ranks top. China leads the world research and application of specialized unmanned machine and underwater robot whose market share of specialized robots in 2017 will be 0.74 billion US dollars and is expected to reach 1.24 billion US dollars billion by 2020.

2.2 State of art in intelligent robotics

Recently, popular intelligent robot products spring up continuously. Research institutes or robot companies in the world have achieved important breakthroughs in many fields, such as dual-arm collaborative robot, intelligent logistics AGV, unmanned driving technology, medical operation and rehabilitation robot, intelligent service robot and specialized robot.

2.2.1 Technological research and application status of intelligent industrial robot

Collaborative robots with the ability of working with people are a typical representative of intelligent industrial robots. Fig. 5 shows some famous human-robot collaborative robots. Barter intelligent collaborative robots introduced by Rethink Company (USA) can finish repeated work independently in factory, as well as collaborating with human workers. They are applicable for material feeding-blanking, controlling machine, packaging and processing material. They can adapt to the changing environment, and excel in small-sized and multi-variety production under the support of "Robot Positioning System". Meanwhile, they are equipped with infrared sensor to detect approaching objects, and the dexterous hands are designed and controlled for collision avoidance[32]. In April 2015, ABB Company developed the Yumi robots consisted of two multi-function intelligent hands and supported by technologies including computer vision, guided programming, precision servo-control and collision-avoidance mechanism, which help to accomplish vision-based guided assembly and force-control assembly, and meet the needs from consumption electronic in-

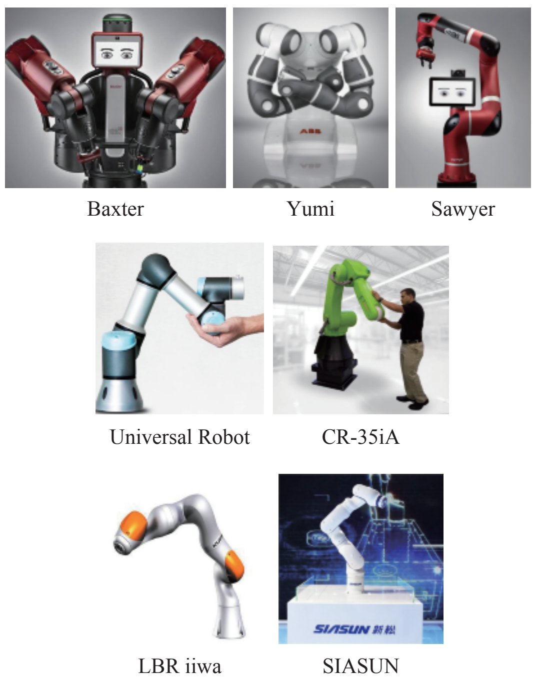


Fig. 5 Famous human-robot collaborative robots in the world[32–35]

dustry for flexible production and manufacturing[33].

In China, SIASUN developed a dexterous multi-joint robot for flexible production with compact arrangement and requiring high precision, which is superior to similar products in loading capacity or production cost[34]. Similarly, there are many other representative robots, including UR series from Universal Robots, CR-35iA from FANUC (with a maximum load of 35 kg), LBRiiwa from KUKA and Automated Item Pick (AIP) technology from KUKA and Swisslog[35].

2.2.2 Technological research and application status of intelligent service robots

In the field of intelligent service robots, foreign countries have advantages in algorithm and technological innovation. Meanwhile, China has achieved outstanding progresses by learning technologies from original equipment manufacturing and exerting efforts on operation and promotion. Fig. 6 shows some typical applications of service robot. Domestic use robots serve as cleaners, family assistant and housekeeper. Currently, main domestic use robots include Roomba series cleaning robot (IRobot Company, USA), XV series cleaning robot (Neato Company), floor-sweeping robot and window-cleaning robot (ECOVACS, China). They have certain intelligence and can accomplish tasks like navigation, obstacle avoidance and path planning. Additionally, Luna (Robo Dynamics Company)[36], Buddy (French Bluefrog Robot Company) and intelligent companion robot (Ainemo, China) can help to deliver things, take care of the elderly and children, and provide reminder and security services.

Fig. 6 Applications of service robots in family, business and research fields[40]

For entertainment and education use, Aldebaran Robotics developed Nao, an education robot equipped with many sensors and adopting an open programming framework. It is further developed so as to be able to make complicated actions like kicking balls and dancing. Moreover, Nao is able to interact with people, a function which could be used to treat patients with autism[37]. Subsequently, Aldebaran Robotics cooperated with Softbank Corporation and developed a new generation of "emotional robot" called Pepper. With voice recognition and facial recognition technologies, Pepper can read emotions and talk with facial expressions and in human's tone[38].

ICub, an advanced humanoid robot developed by Sheffield Robot Institute, whose hands and eyes can coordinate with each other, has a sense of touch and can finish complicated motor and sensory tasks. It can respond to the surrounding environment by voice, actions and collaborative operations. It has been used in more than 20 scientific laboratories in the world and provides a platform to further explore intelligent robot[39]. Jibo, the world first family social-communication robot, not only can talk with people in human's way, but also can serve as family assistant, such as helping in taking family pictures[40].

In China, the 360 Company developed 360 Children Robot which can take pictures for children, sing children's songs and provide educations service based on big data analysis and voice interaction feedback. The Alphal robot, developed by Ubtech, once made dance performance on the Spring Festival Gala, whose second generation has born now. "Yoyo", a commercial robot developed by Beijing Kangli Youlan, has achieved technological breakthroughs in deep voice interaction, facial emotion recognition, motion control and automatic obstacle avoidance, which can provide shopping guidance and teaching supervision[41].

In short-range riding robot, Segway Company (USA) made the first intelligent automatic-balancing traveling robot which was used in spacious environment, such as airport, conference and exhibition center, high-end community and major stadiums. Recently, Ninebot, a domestic short-range traffic company, finished the wholly-owned acquisition of Segway. Its robots, the Wind Runner series and Ninebot series, occupy the world leading positions in both market shares and technological level[42].

2.2.3 Technological research and application status of medical robots

Medical surgery robots can ensure less blood loss, high precision and quick rehabilitation, which own great market potentials[43]. In 1985, Puma 560, the first robot applied to surgery, participated in a brain biopsy operation by providing brain-location service. In 1997, AESOP accomplished the first laparoscopic surgery. It can present a high-precise and consistent operation scene, and offers direct and stable monitoring pictures for the doctor[44]. Intuitive Surgical Company first broke through the challenges caused by accurate 3D visual positioning and master-slave control of robot in surgery, which significantly improved operation view and accuracy. The first generation of da Vinci surgical robot was born in 1999 (as shown in Fig. 7). Now, the fourth generation has been developed. There are nearly 4 000 da Vinci robots in the world. They have accomplished 4 million surgical operations, and are known as the most successful medical surgical robot in the world so far[45].

Fig. 7 da Vinci surgical robot[43]

In addition, DLR Miro developed by DLR Company (Germany) is used in plastic surgery and orthopedic operations. The whole system is portable with only 10 kg[46]. ViRob, an automatic crawl micro-robot by Microbot Medical (Israel) in 2015, can be remotely controlled through electromagnetic wave. It can deliver camera, medicine or devices to narrow and twisted regions in human body, such as blood vessels and alimentary canals, thus assisting doctors in minimally invasive surgery[47].

In China, Robotics Institute of Beihang University and Navy General Hospital cooperated in studying a medical brain surgical robot and achieved breakthroughs in key technologies, such as human-robot synthesis and optimization, medical image processing, navigation orientation and surgery scheduling. Besides, this robot can perform remote operations through the Internet. In 2003, a robot which could assist brain surgery was designed, whose fifth generation has been applied to clinical practice now[48]. In 2013, the "Minimally Invasive Laparoscopic Surgical Robot System", funded by the national "863" plan, was successfully constructed by Robot Institute of Harbin Institute of Technology. It achieved important breakthroughs on key technologies, such as machine design, master-slave control algorithm and 3D peritoneoscope and system integration[49]. In April 2014, "Miaoshou S", the minimally invasive surgical operator system developed by Tianjin University, has finished three operations successfully in Third Xiangya Hospital of Central South University. This is the first time that China has applied surgical robot system into practical use[50]. Chongqing Jinshan Technological Company focuses on the research and development of capsule endoscope. The latest OMOM capsule endoscope can move automatically so as to give doctors more flexible perspectives[51]. So far, Tianzhihang is the largest orthopedics medical robot company in China. The first generation of orthopedics surgical robot (GD-A) was formally registered as a medical equipment in February 2010, filling the blank of related field researches in China[52].

There are some other medical robots which have made contributions to the world. For instance, SpineAssist of Mazor Robotics (Israel) is used for spine reconstruction and mending. The master-slave S-shaped robot CardioArm of Carnegie Mellon University is composed of 102 joints and is applicable for minimally invasive heart surgery. Rosa Brain and Rosa Spine robot of Medtech (France) are used as surgical assistance platforms. Remebot of Beijing Bohuiweikang is applicable for minimally invasive surgical navigation and positioning, and has been passed the quality inspection of CFDA in 2015[53]. NSRS, the first global specialized surgical robot system with inserted motor and developed by Hong Kong Polytechnic University, has been successfully passed the animal clinical test and is going to embrace the market.

2.2.4 Technological research and application status of specialized robot

Specialized robot is a necessary equipment to work in dangerous and tough environment, and a key technology that can release human beings from works carried in aerospace, deep sea, pipeline and works requiring high precision. America takes the leading role in specialized robot. China has made great progresses under favorable policies, especially the research and development of underwater robot.

Recon Scout and Throwbot series, tactics mini robots of Recon Robotics (USA), have advantages of light weight, small size, noiseless, waterproof and dustproof. They are also equipped with infrared optical system and can accomplish reconnaissance missions in military actions. American Army and other military forces in the world have deployed more than 2 200 robots to protect infantry in the war[54]. To solve the problem of power shortage, MIT engineers designed an oil-driven unmanned robot with glider wings, which can fly for 5 consecutive days at low altitude of 15 000 feet with loads from 10 to 20 pounds. It can be applied to ensure communication security and accomplish investigation missions[55]. Guardian S, the latest robot of Sarcos, can be used as outposts in narrow space and dangerous fields, and assist in disaster rescues, special missions and bomb disassembly. It can sustain for 18 hours under regular monitoring mode and 4 hours under continuous motion mode. Audio and video data caught by the head camera can be transmitted to the user end. It is equipped with plenty of sensors and later will install SLAM function to realize self-control[56].

OceanOne is a humanoid robot invented by research team of Stanford University. It adopts a working mode that collaborate artificial intelligence with tactile feedback information, by which the robot can feel the weight and texture of the caught objects, thus adjusting its grasping force. Controller, taking the robot's perspective, can control it by gestures to finish complicated missions. The robot was once used in underwater archaeological work during the time of Louis XIV[57]. Boston Dynamics is devoted to develop advanced robot with high maneuverability, flexibility and fast moving speed. By making full use of sensors and dynamic control, it developed the BigDog for all-terrain goods transportation, the double-feet robot Atlas with ultra-high balancing ability and the Handle with wheel-leg and ultra-strong leaping ability[58](as shown in Fig. 8).

Fig. 8 Representative works of Boston Dynamics[58]

In China, Shenyang Xinsong Company developed the first life detection robot for underground probing and rescue in 2009, which integrates anti-explosion technology and fiber optical communication technology, and reaches the international advanced level on the whole. It can be used to rescue the wounded in accident sites[59]. The Robot Group of Harbin Institute of Technology developed many specialized robots, such as exploder-cleaning robot, wall-climbing robot, pipeline-checking robot and wheel-vehicle-chassis-checking robot[60]. With respect to underwater robot, many national research institutes and enterprises, including 702 Institute of China Shipbuilding Industry Corporation, Shenyang Institute of Automation and Institute of Acoustics of Chinese Academy of Sciences, cooperated together and achieved a series of breakthroughs in deep sea technologies, such as the near-bottom automatic navigation and hover positioning, high-speed underwater acoustic communication, oil-filled silver-zinc storage battery capacity. They designed the deep sea (7 000 m) manned submersible robot "Jiaolong", which hit a new record of diving depth – 7 062 m. Until now, it is the deepest depth in the world. In July 2017, the "Xiang yang hong No.10" scientific research ship carries with China's "Qianlong II" AUV and makes 8 diving operations during 43 times sailings. The operation time is accumulated to 170 hours, the total voyage distance reached 456 km, and the maximum diving depth is 3 320 m, which fully prove the stability and reliability of performance in complicated terrain environment of mid-oceanic ridges[61].

Festo (Germany) is a pioneer in bionic robot research, which developed some representative robots, such as AirPenguin, SmartBird, BionicOpter, BionicKangaroo, BionicANT and eMotion Butterfly that promoted the development of bionic robots. In 2015, Festo cooperated with Beihang University and developed a robot with flexible octopus tentacles, which attracted wide attentions of common people and people from industrial and academic fields[62].

2.2.5 Technological research and application status of unmanned driving

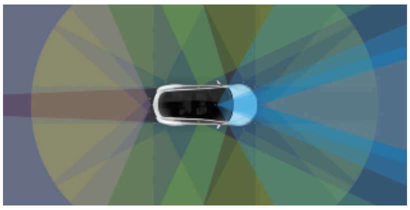
In unmanned driving, according to the report released by Intel Strategy Analytics on July 1st, the value of automatic driving vehicle is expected to reach 7 trillion US dollars in 2050. In addition, that safe and reliable technology will protect a lot of drivers' securities and significantly save commuting time[63]. Great changes will take place in people's travel mode in the future. High-efficient and reliable algorithms, strong manufacture and resource supports, and favorable policies are three necessities for research and promotion of unmanned driving technology.

Google set about doing automatic driving research very early and completed a road test successfully in 2015. It reorganized its automatic driving department in 2016 and then established an independent automatic driving company Waymo. Now, the total travel distance of its automatic driving cars has exceeded 3 million miles[64]. Tesla, an electromobile company, launched an autopilot system in October 2015. Equipped with radar, multiple cameras, ultrasonic radar sensors and DRIVE PX2 processor of NVDIA Company, this autopilot system can realize full-automatic driving. It has an accumulated travel distance of more than 160 million kilometers since applying to practical use[65]. In September 2016, Uber and Volvo Car Group signed a strategic agreement on the development of the next generation of automatic driving technology. They formally launched a pilot program on automatic driving taxi service in Arizona (USA) officially in February 2017[66]. In July 2017, it announced the acquisition of Otto with 680 million US dollars, intending to apply automatic driving services for trucks. The brand new automatic driving set is equipped with a 64-line rotatable laser radar (LiDAR) array and describes the surrounding environment by high-precise point cloud, thus greatly improving the data collection ability and processing capacity of the automatic driving system[67].

In 2017, Tim Cook, CEO of Apple Company, firstly declared Apple's future layout in automobile market: focusing on automatic driving technology research. On April 15th, the Mobile Management Department of California government announced that Apple Company has gained the road test qualification for automatic driving vehicles[68]. In March 2017, Intel Corporation accomplished the acquisition of Mobileye – an Israel company of unmanned driving technology with 15.3 billion US dollars and cooperated with BMW to develop unmanned driving vehicles[69].

In China, Baidu unmanned vehicle project has been implemented for many years. The project started in 2013 and developed an intelligent automobile EU260 with BAIC BJEV in 2016 which can reach "L4 unmanned driving". Later, Baidu launched the "Apollo Program" and announced to open the automatic driving platform, hoping to solve transformation difficulties of traditional automobile manufacturers[70]. In March 2017, Horizon Robotics founded the Autopilot R&D Center in Shanghai to provide autopilot-oriented embedded artificial intelligence software and hardware solutions with high-quality performance, low power consumption and low cost. The core lies in "Hugo"— an automatic driving software system, which has the abilities of perception, prediction, location and decision-making, and is mainly applied to heterogeneous computing platform CPU+GPU or CPU+FPGA[71]. As shown in Fig. 9, more and more companies and scientific research teams join in the competition of unmanned driving technology. It is believed that vehicles with full automatic driving abilities will integrate into people's daily life in the future.

(a) Unmanned driving technological development of Google, Uber and Baidu[64, 66,67,70]



(b) Autopilot system of Tesla[65]

Fig. 9 Fierce competition of driverless technology

2.2.6 Technological research and application status of intelligent logistics robot

With respect to intelligent logistics, warehouse robots represented by intelligent AGV play more and more important role in production applications. Traditional AGV plans routes by electromagnetic path-following system, and avoids barriers by simple sensors, thus ensuring automatic driving along preset routes. Modern warehouse robots integrate RFID automatic recognition technology, laser guiding technology, wireless communication technology and model feature matching technology together, so they can accomplish positioning, guiding and obstacles-avoiding more accurately[72]. Efficiency of route planning and group scheduling is increased significantly by combining with big data, internet of things (IOT) technology and intelligence algorithms[73].

In 2012, Amazon merged Kiva Systems – a logistics robot company by 775 million US dollars. It deployed Kiva robots in all warehouses (as shown in Fig. 10). Kiva can help to pick items automatically by moving target goods shelves for warehouse staffs who are responsible for final item picking, thus saving their time for walking and finding. The robot can run for 30 miles per hour and the picking accuracy rate can reach 99.99%. It breaks the traditional working mode in e-commerce logistics center of "people finding goods and shelves", and realizes the new mode of "goods and shelves finding people", thus significantly saving labor cost and increasing allocating efficiency. One report in 2013 showed that delivery cost of an ordinary order at that time was about \$3.50 to \$ 3.75, but the cost decreased by 20%–40% after the application of Kiva robot. It is estimated that Amazon can reduce about 900 million US dollars cost in goods picking[74].

Fig. 10 Item picking of Kiva robot in Amazon warehouse[74]

In China, companies including Tmall, JDcom and STO Express all turn to use warehouse robots. In Alibaba's warehouse in Tianjin, 50 Geek+ warehouse robots developed by Beijing Jizhijia Technology Corporation are deployed to assist in item picking. The daily delivery capacity is over 20 000 orders and it can replace more than 40 workers. The robots even entered Japan in 2017, marking a step into the international market[75]. Shanghai Kuaicang Intelligence Technology Corporation became the largest warehouse robot company after raising the Series B round. It then developed and applied the Kuaicang robot system to Vipshop and JDcom. Each warehouse is equipped with 100 robots which are able to deal with 40 000 to 50 000 orders a day and the maximum daily delivery capacity per warehouse can excel 100 000 orders[76]. Intelligent item picking robots and "Qianmo" intelligent warehouse system developed by Hangzhou Haikang Robot Company are applied to the 2 000 m^2 warehouse of STO Express in Linyi, Shandong Province. They can fast pick small parcels (<5 kg) after weighting and code reading by the help of fast code reading technology embedded in the industrial camera and intelligent item picking system. Based on QR code and customized navigation, they can deliver parcels along the optimal path according to the commands of robot scheduling system. Its efficiency is up to 20 000 parcels per hour[77].

According to the prediction of Tractica, the global market value of logistics robot will reach 22.4 billion US dollars in 2021, indicating a coming explosive growth of robot market[78]. Except for the above robot enterprises, there are many other companies, such as GreyOrange (India), Exotec (France), Fetch Robotics (USA), Clearpath Robotics (USA), Locus Robotics (USA), Magazino (Germany), Swisslog (Switzerland), Shenzhen Oukai Robotics, Xinsong Robotics, Beijing Shuiyan Technology, Hangzhou Nanjiang Robotics, etc.

In addition, Amazon firstly accomplished goods delivery by commercial unmanned vehicle in December 2016[79]. YaraBirkeland, the first unmanned cargo ship developed by Yara International ASA and Kongsberg Gruppen, is planned to be used in 2018 which can realize automatic navigation under the support of global position system (GPS), radar, camera and sensors even when many other ships travel around. In the long run, it can save as high as 90% operation cost from fuel consumption and labor cost.

3 Key and leading technologies of intelligent robots

According to the degrees of maturity, universality and urgency, there are key technologies and leading technologies. Most of the above mentioned robots have realized industrialization. China's intelligent robots have achieved breakthroughs in some key technologies, but the overall core technologies still fall behind some leading countries in the world.

To strengthen the competitiveness of Chinese robot brands and products, it is suggested to make deep research on the following technologies: new rigid-flexible coupling bionic compliant mechanism, safety decision mechanism oriented to human-robot integration, vision-based image understanding and low-cost SLAM technology under non-structural environment, traffic information collection technology, distributed cooperative control of multi-agent system, medical virtual-real and immersive human-robot interaction, multi-modal medical image registration and integration technology, human-robot coupling and implementation technique for wearable devices, as well as emotional recognition and interaction mechanism oriented to harmonious human-robot cooperation. Research and innovation on leading technologies are important for the formation and development of national emerging industries in the future. The following text will focus on brain-computer interface (BCI) technology, brain-like robot control and decision-making technology, new material application oriented to soft structure, and network decision-making mechanism based on cloud computing and big data[80].

3.1 Key technologies of intelligent robot

3.1.1 Human-robot collaboration technology

Human-machine collaborative robot plays an even more important role in the new generation of intelligent robots. ISO issued the latest production standards of collaborative robot in 2016[81]. To realize harmonious coexistence, new human-robot cooperation robot should be guaranteed in safety, comfortability, adaptation and easy-programming. Safety means to protect people from possible injuries caused by robots during interaction. Comfortability means actions of robot have to conform with the cognitive habits of people and people can recognize robot's intentions. Adaptation means that robot can understand people's demand and adapt to people's motion and different missions accurately. Easy-programming means that it should be easy for people to program, to learn the operation methods and to easily control the robot.

Human and robot can interact by natural language, visions and tactile contact. Key technologies that have to be mastered include design of rigid-flexible coupling rigidity-variable mechanism[82–84], safety decision-making mechanism oriented to human-robot cooperation[85, 86], 3D holographic environment modeling[87], high-precision tactile and force sensors, and image analytical algorithm[88–90]. On the one hand, the harmonious coexistence of man, robot and environment shall be ensured. On the other hand, considerations shall be given to robot's adaptability to different environments and missions, thus realizing high-efficient human-robot collaboration.

3.1.2 Autonomous navigation technology under non-structural environment

Autonomous navigation technology has been the research hotspot in the development of various robots, such as transfer robots on production line, logistics robots for efficient automatic warehouse management, mobile service robots in shopping malls, exhibition halls and families, as well as the promising driverless vehicles.

It is difficult to realize high-efficient safety positioning, obstacle avoidance and navigation in non-structural environment with both static and moving obstacles. That involves some key technologies, such as low-cost SLAM technology[91], multi-sensor information collection and integration technology, vision-based image understanding technology in non-structural environment[92], intelligent traffic control technology[93], etc.

Higher requirements on sensing, perception and decision-making are proposed to driverless automobile for the consideration of safety and wide application. GPS/IMU sensing system accomplishes self-positioning of unmanned vehicle by global positioning and regular updating data. Laser radar is used as the main sensor for drawing maps, assisting in positioning and avoiding obstacles. Camera is widely used in different scenes, such as object recognition and object tracking, which is the major solutions to lane detection, traffic light detection and sidewalk detection. Radar and sonar system is set as the last safeguard to make sure the effectiveness of obstacle avoidance.

Laser radar generates point clouds for "shaped description" of surrounding environment and reports accurate location by combining particle filtering with the present map and observation data. Meanwhile, stereoscopic measurement is also used to assist in positioning. According to the pixel and depth information from laser and visual pictures, a large CNN neural network is established and offline training is performed by deep learning technology in order to recognize and track vehicles, pedestrians and trees on the road[94].

For decision-making, an appropriate probability model is constructed to predict dynamic behaviors and make route planning of people and vehicles. A two-layer obstacle avoidance mechanism is established to ensure the safety driving of vehicles. The first layer is a prediction layer based on traffic conditions and the second layer is a real-time response layer based on radar data. They are respectively used for overall route correction and partial route correction[95].

3.1.3 Multi-agent robot system

Multi-agent robot system refers to a certain quantity of independent agents move and cooperate as one ordered and self-organized entity. Such cooperative action can help the group to realize certain complicated functions, which shows an explicit tendency towards collective "intentions" or "goals"[96].

Researches on multi-agent robot system mainly focus on the following aspects: accelerating convergence of coordinated control and realizing finite time control[97], switching topological structure in time-varying system and describing multi-agent network in a more reasonable way[98], designing estimation program under global nonlinear collaborative state, and realizing distributed collaborative control of group robots based on heuristic algorithm[99].

Compared to traditional single-agent robot system, there is no global control but distributed control in multi-agents robot system. The collaboration of multi-agents improves efficiency when executing missions and its redundancy enhances robustness of the system which can accomplish distributed tasks that single-agent system cannot finish. Moreover, multi-agents robot system is easy to be expanded and updated. Each agent has relatively simple functions and limited abilities of information collection, processing and communication. Through information transmission and interaction among agents, the whole system will be highly efficient in collaboration and show high-level intelligence, thus accomplishing various tough and complicated tasks that require high precision and beyond the competence of single-agent robot system[100]. Multi-agent robot system shows great power in multi-sensor collaborative information processing, multi-robot collaboration, unmanned aerial vehicle team, multi-manipulator operation control and other fields[101–103].

3.1.4 Emotion recognition and interaction mechanism of robot oriented to harmonious human-robot cooperation

Emotion recognition and interaction is to give computer or robot human emotions through artificial method and technologies, thus making them be able to express, recognize and understand emotions as well as imitate, extend and expand human's emotion. As a result, a harmonious human-robot environment could be built, and the robot would gain higher intelligent[104].

Three technologies have to be deep studied, namely, emotion computing, emotion modeling and emotion recognition technology. Emotion computing refers to establish a computer system for perceiving and recognizing human emotions based on the information that arouse and influence human emotions. Human emotional information that is explicitly available include extrinsic emotional information, such as voice, gesture and facial expression[105], and intrinsic emotional information, such as heartbeat, pulse, breathing and body temperature. Two key questions of emotion computing are: How to match these expression signals with emotional characteristics, and how to determine the proportions of different emotional information[106]. Emotional modeling is an important part of emotional simulation study, which has achieved some preliminary research progresses. Representative models are OCC emotional model that reflects cognition of human emotions and divides emotional stimuli into 22 classes[107]; intelligent agent model that integrates environmental data[108]; EMA model that guides agent to take actions in accordance with people's emotional state by building a human-like response strategic mechanism; HMM model based on probability statistics[109]. Emotional recognition technologies include: 1) facial expression recognition technology based on machine vision, which analyzes human feelings and emotions by capturing human facial muscle changes through image processing[110]; 2) automatic speech recognition and natural language processing technology of which establishing rich and high-quality emotional corpus database and associating emotions with acoustic features are research hotspots[111]; 3) physiological emotional recognition technology which requires further studies on how to timely acquire rich and stable physiological signals and establish a multi-pattern emotional signal model. By combining leading technologies like human-robot interface technology, artificial intelligence reasoning and cloud computing, the emotional recognition and interaction technologies will be applied to even wider fields and play a more and more important role in the future.

3.2 Innovative leading technologies of intelligent robots

3.2.1 BCI technology

BCI means that commands from human brain can be directly transmitted to the appointed machine terminal by collecting, recognizing and transforming the electrical activity of nervous system and the characteristic signals. It has great innovative significance and application values in the human-robot communication field and is conducive to realizing efficient and convenient robot control and operation. The technology is going to be used in the fields of disease rehabilitation, disaster rescue and entertainment industry.

Researchers from American Duke University implanted microelectrode array to the motor nerve control area in macaca arctoides' cerebral cortex. They measured, analyzed and decoded the real-time multi-channel EEG signals, established a model for predicting motion state, and accomplished operating control on robot arm based on the multi-channel EEG signals. *Nature* made a series of reports on the above results[112, 113]. The researchers of DEKA arm program, a program funded by DARPA, introduced on *Nature* that the motion ability and independent living ability of the paralyzed can be recovered by establishing a neural interface which can translate the neural activities of cerebral cortex into control signals of motion-assisted device. Researchers also proved that people who have long-time suffered from paralysis or Central Nervous System damage can recover ability by controlling complicated devices through neural signals[114].

Nick Ramsay team from Medicine School of Utrecht University (Netherlands) made the first experiment on human BCI. They implanted the full-embedded BCI into one patient with late amyotrophic lateral sclerosis (ALS). After training, the patient can accurately and independently control a computer typing program as a mean to communicate with people[115]. In 2013, Paralysis Recovery Research Plan from Ohio State University implanted the chip that connects hundreds of neurons with the brains of paralyzed people. The chip can bypass the damaged spine and directly transmit brain commands to hand muscles so that the amputated patients can control artificial limb successfully[116]. By implanting 2 cerebral motor cortex recording chips and 36 electrodes, BoluAjiboye team from the Case Western Reserve University helps patients in eating, fetching objects and doing other simple actions by controlling the robot arm[117, 118].

With the progresses of biological signal measurement and BCI technology, more advanced BCI devices like electro-photoluminescence system for invigorating muscle functions, embedded artificial visual system and artificial auditory system will enjoy a promising application prospect in the future.

3.2.2 Brain-like robot control and decision-making

With robots' deeper involvement in industrial production and social life in the future, people will raise higher requirements for its performance. Since robots serve in complicated and changeable environment with disturbances and uncertainties, and the tasks are high-dimensional and nonlinear, it is far beyond the validity and effectiveness of traditional control algorithms.

With supports of rich sensor data, robots can perform well in effective data classification and summarization, and extract reliable effective data in the future. The robots own strong learning abilities which can be divided into supervised learning and unsupervised learning. The supervised learning trains reasonable model parameters based on artificially labeled sample set, thus making corresponding control decisions. The unsupervised learning trains the optimal control law from unlabeled sample set without prior knowledge[119].

Supervised learning mainly focuses on robot's learning by imitation and from demonstration[120, 121]. Alexandros Paraschos et al.[120] proposed the probability motion primitive (ProMP), described the motion primitive by probabilistic model, and enabled robots to adapt changing tasks. In some studies[122, 123], motion primitive constructs a compact expression of robot's control laws, which is used to take actions like colliding, knocking and seizing. Robots can imitate people's actions and adapt to different scenes by adjusting motion primitive parameters.

Unsupervised learning mainly concentrates on constructing complicated neural network and deep learning. Deep learning is primarily proposed by Hinton et al., which mainly simulates feature learning process of human brain by using neural network. Levine et al.[124, 125] implemented unsupervised learning of robots by establishing a large CNN neural network. Robot can extract features during the training process and map relationship among robot motion, sensor information and tasks, thus helping robot finishing tasks without human interference, such as opening and closing doors, and grasping items (as shown in Fig. 11). Based on the brain's multi-layer abstract expression mechanism, such unsupervised feature learning realizes deep abstract expression of initial features and avoids artificial interference during the process of feature extraction. Meanwhile, deep learning, to some extent, solves the problems of local convergence and over adaptation in traditional artificial neural network.

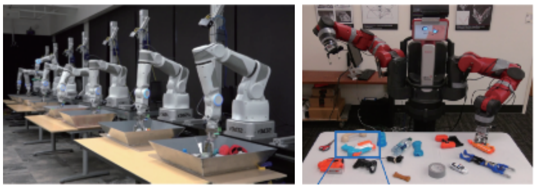


Fig. 11 Robot training of object grasping based on deep learning[124, 125]

3.2.3 Material cross-innovation and applications of robot oriented to software structure

Traditional robots mainly have a rigid body with complicated structure, limited flexibility and poor safety and adaptation abilities. With the development of 3D printing technology and new intelligent materials, soft robots made of soft or flexible materials are developed. Fig.12 shows the Soft gripper developed by Festo and BUAA. Theoretically, they can realize continuous deformation and have infinite degrees of freedom (DOFs)[126, 127]. They possess huge advantages in human-robot cooperation, grasping complicated and fragile goods and working in small spaces[128–130].

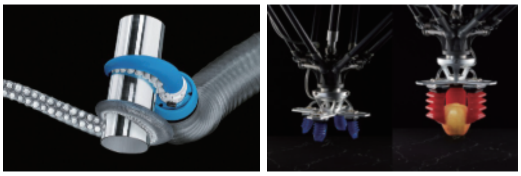


Fig. 12 Soft gripper developed by Festo and BUAA[126, 127]

Researches on bionic structures can be divided into three types: 1) researches on traditional pneumatic and cable-driven structure, such as the Trunk robot[131] and pneumatic muscle[132] of Festo; 2) researches on the combination of super-elastic and high-ductile silica gel materials and the latest 3D printing technology. These structures are mainly pneumatic and are widely used in catching, holding, bionic and medical robots; 3) researches that aim to realize complicated 3D motions through intelligent materials, such as shape memory alloy, shape memory polymers and dielectric elastomer which are embedded into soft materials so as to make deformation generated by external physical fields[133]. That structures have already been applied to the bionic creeping robot Meshworm developed by RUS team from MIT which arrange SMA to a network structure, and the multi-gripper octobot designed by Italian bionic laboratory.

Voltage-varying drive mode based on fluids enjoys a promising application prospect[134]. How to reduce the device size, expand application range under non-structural environment and construct nonlinear system model under fluid control are research hotspots. With deformation of intelligent materials in electric field, thermal field or magnetic field, integrated design of driving-ontology of soft robot can be realized. However, how to create a safe, stable and controllable physical field is the key to realize reliable and effective driving.

In addition, researches on soft robot are facing the following key challenges: 1) production technique that can generate complicated 3D cavity structure, such as shape deposition manufacturing (SDM) and multi-material 3D printing; 2) development of embedded high-precise sensor which won't influence mechanical characteristics of ontology, such as conducting liquid and optical fiber; 3) improvement of strength and rigidity-variable and rigid-flexible coupling of soft robots while ensuring ontology deformation capacity.

3.2.4 Network decision mechanism of robot based on cloud computing and big data

On the Humanoids 2010 international conference, J. J. Kuffner[135] proposed the concept of "cloud robot" for the first time. Cloud robot is the combination of cloud computing and robotics. Cloud computing is a compute mode based on the Internet. The shareable software and hardware resources and information can be offered to network terminals according to demands. As the network terminal, robot does not need to store all data or own ultra-strong computing ability, but to link related servers to take necessary information.

Cloud robot not only can upload complicated computing tasks to the cloud end, but also can receive massive data and share information and skills. It has stronger abilities of storage, computing and learning and makes resource sharing among robots more convenient. Besides, robots have smaller burdens under same or similar scenes, thus saving time of developers for repeated work[136].

Key technologies that needed to be mastered include Map-reduce computer group, service-oriented architecture (SOA), RaaS model, wireless radio wave and microwave communication technology, as well as WiFi and Bluetooth technologies. Many scientific and technical corporations like Microsoft, Google and Baidu have participated in researches of cloud computing and big data. Various cloud robot service platforms have been proposed, such as cloud service platform based on network robot (e.g., ROS platform[137] and RoboEarth platform), cloud service platforms based on sensor network (e.g., Sensorcloud[138] and X-sensor), cloud service platform based on RSNP model (e.g., Jeeves platform)[139]. Development of cloud computing and big data will promote the development of robot field, such as SLAM, object grasping and emotional understanding. Significantly, Singapore ASORO Laboratory has constructed a cloud computing architecture that helps robots to construct a 3D map of the current environment at a far quicker speed than robot-mounted computer[140]. B. Keho et al. from University of California, Bekeley accomplished the grasping task through 3D robot based on cloud platform by using PR2 robot from Willow Garage Company and target recognition engine from Google[141]. Microsoft developed a virtual individual assistant Cortana on the Build Conference which depends on cloud architecture and can make complete dialogue with people. During conversation, it can judge whether it is the same speaker or not. DeepMind team from Google developed and improved the AlphaGo artificial intelligence system which defeated many top Weiqi masters in the world[142].

Cloud robots, with unique advantages and supported by cloud computing and big data technologies, will arouse new reforms in the field of intelligent robots.

4 Prospect of and reflection on intelligent robot

With the deepening of industrial reform, changes of social demands and technological progress, the global robot market is undergoing an explosive growth. Countries in the world compete in raising robot development strategies. The third platform technologies represented by cloud computing, big data, mobile and social contact drive the development of global robot industry toward intelligence, innovation and digitization.

In the robot industrial transformation process, intelligent robots play a dual role. It is the representative of traditional manufacturing industry, and it also plays an important role in accelerating and promoting innovations during the process of transformation.

The new generation of intelligent robot will have the characteristics of connectivity, virtual-real integration, software definition and human-robot integration. Specifically, it can collect various data by multiple sensors and upload them to the cloud end for primary processing, thus realizing information share. Virtual signal and real equipment are integrated deeply, forming a closed procedure of data collection, processing, analysis, feedback and execution, and implementing "real-virtual-real" conversion. The intelligent algorithm for massive data analysis depends on excellent software applications, which stimulates the new generation of intelligent robot to develop in a software-oriented, content-based, platform and API centralized way. The robot can realize human-robot cooperation based on image and video, and can even read human′s psychological activities and make affective communications through deep learning.

China is the largest robot market in the world. With the promotion of national strategy and the development of industrial chain, many organizations and individuals participate in robot industrial constructions which collect strengths from governments, companies, universities, research institutes, users and investors, laying a good foundation for positive and sound development of robots. The intelligent robot industry is gradually scalable and systematic, basically forming a complete industrial chain and welcoming outstanding technological innovation fruits. The intelligent robot market embraces a great development opportunity. However, it still faces abundant challenges, including bottlenecks in key and leading technologies, limited innovation and promotion of intelligent robot applications, inadequate resource integration and collaboration, etc.

With respect to key and leading technologies, existing intelligent robots have low intelligence and relatively simple functions. They behave poor in human-robot cooperation under complicated scenes and are difficult to meet users′ demands. It is urgent to overcome technological bottlenecks to achieve endogenous growth. Firstly, in human-robot cooperation, research and development on key technologies like multi-modal perception, environment modeling and decision-making optimization shall be accelerated in order to strengthen human-robot cooperation and collaboration. Secondly, robot technologies shall deeply integrate with the Internet of Things, cloud computing and big data technologies, and massive sharing data and computing resources shall be fully used, thus extending the service ability of intelligent robots. Moreover, artificial intelligence technologies like image recognition, emotional interaction, deep learning and brain-like intelligence have to be further developed and used to create robots with high-intelligent decision-making abilities, and safety and reliability insurance. Besides the above technological bottlenecks, there emerge some new challenges in the way of robot technological breakthroughs: How to make full use of the industrial chain to realize collaborative research and development; How to improve the robot′s operation system; How to find innovative methods to smooth cross-field integration.

For applications, it is necessary to cultivate absolute demands and follow the development tendency of the market. With the widely applications of robots, user demands are diversified and personalized. However, there is no effective product feedback channel between products and users. The lack of related deep knowledge and poor understanding on users′ demands increase the difficulties to build a bridge between supply and demand. Additionally, users are more inclined to personalized, innovative, diversified and fast-operated products. As a result, it is necessary to make continuous research and development on technologies and products, as well as continuously collecting product feedbacks, with intentions to reduce production cost, resist price barriers, form rich product lines, increase external designs investment, and finally attract more new users.

Lastly, the benefits of intelligent robot are exaggerated. Investors are easy to be short-sighted, with hopes of achieving quick success and instant benefits, which would misguide the design of mid and long-term layout, spread false signals of demands, and hinder deep and sustainable development of the robot industry. Therefore, following market trends, understanding users′ key demands, considering long-term development, and raising innovative scenes-based applications have become important tasks that intelligent robot industry have to finish.

Concerning with resources, China′s robot industry is still at the initial stage. More and more industrial users, ICT enterprises and new corporations join in the robot industry, which increases the complexity of robot ecosystem. All these involved parties vary in development and have different interests in and appeals to robots. They are relatively independent with each other and are struggling with different problems in capital, productivity, market experiences and core components supply. As a result, it is extremely difficult to integrate all the parties together. The communication mechanism between government and emerging enterprises still has to be perfected. Research fruits of academic institutes and product development of enterprises are separated with low conversion rate of research results. Due to low participation rate of individual and commercial users in the industrial chain, there lack of customized and demands-based robots. Investors pay few attentions to leading technologies, resulting in separation of capitals and basic researches. How to create an open and efficient collaboration system, reasonably allocate and use high-quality resources, and further improve the development ecosystem are other challenges of China′s robot industry.

In a word, to overcome the above problems and challenges, China′s robot industry has to create a new, open, innovative, organic, collaborative and sound ecosystem so as to attract more parties join in with open minds, thus reaching a win-win situation by sharing resources and high-efficient collaborations. Detailed suggestions on policy supports, technological breakthroughs, and applications and promotions are followed below.

4.1 Suggestions on policy supports

The government should make long-term development plan for intelligent robot industry, continuously optimize top-level design, and maintain policy′s consistency and sustainability. Besides, determine strategic development direction and implementation method of robot industry, give adequate guidance for market and capital and avoid short-sighted misunderstandings. The policies and programs in government working reports which are related with artificial intelligence and intelligent robots shall be effectively implemented. Those programs deserve priori supports, and require more endeavors to achieve breakthroughs. Related standards and management methods shall be perfected so as to normalize industry supervision and high-efficiently allocate and utilize resources. International investment and talent introduction channels should be established, and the talent guarantee mechanism should be perfected. What′s more, the government shall seize the highland of technique and talent, and integrate high-level academic institutes, backbone enterprises and leading users to absorb their advantageous resources, thus promoting a new collaboration mode of "industry, university, research institutes and users", and realizing coordinated progresses of knowledge technologies and market products.

4.2 Suggestions on technological breakthroughs

Determine and focus on several key technologies that will greatly influence robot industry development so as to concentrate dominant resources on those key techniques and core processing technologies, as well as solving the problems of standardization and modularization. Special studies on leading technologies like human-robot cooperation, automatic navigation, new sensor, biological-mechanical-electrical integration and artificial intelligence shall be carried out. Enterprises shall increase investment to the research and development of machine vision, brain-like machine learning, big data analysis, and other artificial intelligence related fields, and accelerate their deep integration with robot technologies to solve emotional and functional interaction problems between robot and human beings. The open cooperative innovation system of "industry, university, research institutes and users" shall be fully used to overcome technological difficulties. Effective communication and feedback mechanism between leading technologies and product demands shall be established to increase conversion rate of technological research fruits, shorten conversion period and promote technological updating and progresses in the process of production and application.

4.3 Suggestions on applications and promotions

Deep market investigation shall be made to explore market potentials and users′ real demands. Attentions shall be also given to the classification and extension of the emerging robot market. Besides, the industrial chain has to be enriched to meet users′ diversified demands on one hand, and develop absolute robot demands in subfields like logistics, driverless automobile, medical care, entertainment, education and rescue on the other hand. A product model base shall be established to facilitate technological and experience communication among enterprises, and individuals and users shall be involved so as to form a benign interaction mechanism between the upstream and downstream of the industrial chain. It is suggested to construct a robot cloud platform, establish effective data collection and analysis mechanism develop cloud-based software and application programs, and create a cloud market of robot application software. What′s more, the safety mechanism of robot shall be perfected, providing corresponding safety insurances for different entities and procedures related to production, equipment, network and data.

5 Conclusions

With development of intelligent hardware and artificial intelligence technology, intelligent robots have achieved outstanding progresses and are widely used in collaborative robot, logistics, unmanned driving, medical care, education and entertainment. Diversified user demands and increasing emergence of new technologies drive robot to develop in a high-intelligent, high-adaptive and network-based way. The age of intelligent robots has arrived. As the largest robot market in the world, China is going to embrace great development opportunities, as well as massive challenges. At present, the development of China′s intelligent robots still fall behind the world advanced level. It is necessary to understand the situation, determine development status and goals, formulate strategic policies conforming with China′s national conditions, overcome key technologies like core components, new sensor, human-robot interaction and artificial intelligence, master the market trends, establish an effective monitoring and safety mechanism, and smoothly accomplish transformation and upgrading of intelligent robots. It is believed that the great wish of "robot popularization" will be realized in the near future with government′s supports and investment, and continuous efforts of scientific researchers.

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